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MODULUS OF ELASTICITY OF ROCKS:

AND

VELOCITIES OF SEISMIC WAVES:

WITH

A HINT TO THE FREQUENCY OF AFTER-SHOCKS.

BY

S. KUSAKABE, *Rigakushi.*

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With Plates I.—XIV., Containing 73 Figures.  
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May. 1904.



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MODULUS OF ELASTICITY OF ROCKS :

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VELOCITIES OF SEISMIC WAVES :

WITH

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BY

S. KUSAKABE. *Rigakushi.*

1. Introduction.

The present experiments, the expenses of which were defrayed by the Earthq. Inv. Committee out of the fund specially allotted for the investigation of the elastic properties of rocks, serves as a complement to the note, recently published by the author, on the modulus of rigidity of rocks.* Some of the specimens were one and the same with those used in the last investigation, and the others were prepared also in a similar manner. The principal object of the present investigation is not to determine any accurate value of the modulus of elasticity, but to determine whether the modulus is constant within tolerably wide limits or not, and if it is not constant, how it varies with the amount of stress or with time, and other factors which affect the change. The modulus is measured by the method of flexure; but the apparatus is not so simple like one which is generally employed. It would not be therefore superfluous to describe the details of the apparatus in the next section.

2. Arrangements and Flexure-apparatus.

In the measurement of flexure, the methods of cathetometre or of

* This Publication. No. 14. 1903. Tōkyō. The Jour. of the Col. of Sci., Imp. Univ. of Tōkyō, Japan. Vol. XIX, Art. 6. 1903.

mikrometerscrew are generally put aside. The method of mirror and scale, Fig. 1, Pl. I, as modified by A. König,* is generally adopted though that of optical interference is more accurate. The apparatus as designed in the present experiment combines the advantages of König's arrangement with other necessary appliances. The principal features of the improvements are:—(1) to bend the specimen cyclically from one side to the other, with increasing and decreasing force passing through zero continuously; (2) to eliminate any external disturbance such as minute rotation of the specimen or slight displacements of the scale and telescope.

First arrangement:—A rough sketch of the first arrangement is shown in Fig. 2, Pl. I. The specimen is placed horizontally and bent righthandedly or lefthandedly, so that the plane of curvature is horizontal. There are necessarily four fulcrums and two scales instead of two and one respectively. As in König's method, the twice-reflected image of the first scale S_1 is seen in the field of the telescope T ; and beside this an image of the second scale S_2 , once reflected by the mirror M_2 is also to be seen.

Second arrangement:—In Fig. 3, Pl. I, the second arrangement is shown in its rough sketch. As in the first arrangement, the specimen is placed horizontally and, when it is bent, its plane of curvature is also horizontal. There is only one scale; but two more mirrors M_3 and M_4 are rigidly fixed to the support, while M_1 and M_2 are attached to the specimen. Four different images of one and the same scale S could be seen in the field of the telescope T , Fig. 4, Pl. I. They are all reflected twice by the following mirrors respectively:—

Right upper image	reflected by the mirrors	M_1 and M_2 ,
Right lower	„ „ „ „ „	M_1 and M_4 ,
Left upper	„ „ „ „ „	M_3 and M_2 ,
Left lower	„ „ „ „ „	M_3 and M_4 .

* A. König. Ueber eine neue Methode zur Bestimmung des Elasticitäts moduls. Wied. Ann. 28, 1886.

Flexure Apparatus.—In Pl. I, Figs. 5 and 6 show front and side-view of the flexure apparatus while Fig. 7 shows it in the plan. The two mirrors M_1 and M_2 rotate as the specimen is bent, while the other mirrors M_3 and M_4 are fixed unless the apparatus itself is displaced. The fulcrums F_1 , F_2 , F_3 and F_4 in Fig. 7 are so adjusted that the edges of any two of them lie in a vertical plane. A small frame-work F, which is shown in Figs. 6 and 7 and more minutely in Fig. 8 Pl. II, serves to apply bending force to the specimen. The frame-work consists of two wedges, one fixed (W_1) and the other movable (W_2) inside a proper case. After having put a specimen between the two wedges, the movable wedge W_2 can be pushed firmly against the specimen by a fixed screw S . In the extremities of the strings S_1 and S_2 , which run over small pulleys P_1 , P_2 etc. to the neighbourhood of the observer, some weights are hung which give the bending force. The support of the fulcrums is made of soft iron, which is rigidly screwed on a wooden block. From Fig. 5, Pl. 1, it would be easily seen that, when equal weights are hang on both S_1 and S_2 , no bending force acts on the specimen, and that it is the difference of weights hang on the two strings which is effective to bend the specimen. That is to say, if m_1 and m_2 are the two weights hang on the two strings S_1 and S_2 respectively, then their sum $m_1 + m_2 = M_0$ resists the action of the bending force, the last of which is due to their difference $m_2 - m_1 = M$. For future reference, M_0 and M will be called the Resisting mass and the Effective mass respectively.

When the effective mass is positive, i.e. as more weight is hang on the string S_2 than on S_1 , the specimen is supported by the fulcrums F_3 and F_4 , and it becomes convex towards the righthand side. In the other case, it becomes convex towards the lefthand side, supported by the fulcrums F_1 and F_2 . The fulcrums standing face to face, i.e. F_1 and F_3 or F_2 and F_4 , are clamped not to push too tightly against the specimen, as there is a possibility of the bending of the specimen being hindered by friction.

A telescope, provided with a micrometer-screw, is rigidly clamped

on a tripod. The scale, engraved on a ground-glass plate, 20 cm. long and 2 cm. wide is covered by a black board having a slit, 8 mm. wide, and is illuminated by a row of small gas flames.

3. Order of Observation.

Order of observation is generally as follows :—

1. To begin with, equal weights, each $\frac{1}{2} M_0$, are hang on the strings S_1 and S_2 .

2. A specimen is put between the fulcrums, passing through the framework F' , the last of which is to be clamped on the middle part of the specimen. The planes passing through the edges of the fulcrums standing face to face should be normal to the length of the specimen.

3. The mirrors are so clamped in their proper positions that the images of the scale reflected by them stand side by side within the field of the telescope. This adjustment requires much experience.

4. The constants of the micrometer-screw for all images are determined. They are nearly equal to each other but not strictly. One mm. of the scale division is equal to about 20 divisions of the micrometer-screw, which is again equivalent to rotation of 5.176×10^{-6} rad. = $1''.968$.

5. Zero-readings are taken for all images in a fixed order ; i.e. (i) right upper image, (ii) right lower image, (iii) left upper image, (iv) left lower image.

6. The suspended weights consists of some fourty pieces of equal weights. A definite number of pieces, say $\frac{1}{2} m$, was taken off from one string and added on the other. The bending force due to this is obviously mg , where g represent the value of gravity. The time-record corresponding to this transposition of weights is taken.

7. After a certain time, the readings are noted for all images in the same order as in the case of zero-reading.

8. Second transposition of weights ; the time recorded ; scale

readings noted ; and so on till a definite amount of bending forces is reached.

9. The weight is then transposed in the opposite way so that the force diminishes gradually and ultimately becomes oppositely directed. In this way, a series of observations are made to complete the cyclic process several times.

10. From the amount of the deviations of the images, the amount of bending due to corresponding force are calculated, by a process to be explained in the next section.

4. Process of Calculation.

Process of calculation naturally divides itself into two according as the first or the second arrangement is adopted.

For the first arrangement we have :— In Fig. 9, Pl. II, let

SPE be the initial position of the specimen,
 Sm_1 and Em_1' „ „ „ „ „ mirrors M_1 and M
 respectively,

a and AB be the initial positions of the scales,

T be the position of the telescope.

Suppose, for the first case, the effective mass M to be positive so that the specimen takes the position $SP'E$ and the mirror Sm_1 and Em_1' takes the positions Sm_2 and Em_2' , rotating through an angle $\pm\alpha$ respectively. And also suppose, then, the specimen to be rotated through an angle β so that the last positions of the mirrors are $S'm_3$ and $E'm_3'$ respectively. Note that the rotation of the specimen is generally not negligible, although the fulcrums as well as the apparatus itself are absolutely fixed. If the specimen be perfect square prism and the plane passing through the edges of the fulcrums F_1 and F_2 or F_3 and F_4 perpendicular to that passing through those of the fulcrums F_1 and F_3 or F_2 and F_4 , the specimen can not rotate. The above condition, however, could not be satisfied in the actual case, so that the specimen rotates whenever the effective mass changes its sign.

Let $\overline{MM'} = c$, $\overline{AM'} = D$, $\overline{Ma} = d$, then it may be easily seen that

$$4a = \text{arctg} \left\{ \frac{1}{d} \left(\overline{ab} - \frac{c}{D} \overline{AB} \right) \right\}$$

$$\text{or } 4da = \overline{ab} - \frac{c}{D} \overline{AB} - \frac{1}{3} \frac{1}{d^2} \left\{ \overline{ab} - \frac{c}{D} \overline{AB} \right\}^3 + \dots$$

Now, in so far as the present experiment goes, the first two terms in the righthand member are only effective: e.g. for the case of a piece of sandstone which seems to be one of the rocks having the smallest modulus of elasticity, we had

$$M = 3000 \text{ grams, } \overline{ab} = 3.139 \text{ cm., } \overline{AB} = 1.525 \text{ cm., } c = 12.8 \text{ cm.,} \\ d = 235.3 \text{ cm., } D = 248.5 \text{ cm.}$$

$$\text{so that } \overline{ab} - \frac{c}{D} \overline{AB} = 3.060, \quad \frac{1}{3} \frac{1}{d^2} \left\{ \overline{ab} - \frac{c}{D} \overline{AB} \right\}^3 = 0.00017.$$

Thus, the magnitude of the third term, and *a priori* all the following terms, is within the errors of observation. Hence we have

$$a = \frac{1}{4d} \left\{ \overline{ab} - \frac{c}{D} \overline{AB} \right\}.$$

It may be easily proved that, in other cases where either the curvature or the rotation of the specimen or both of them change their signs, the same formula holds good, provided $\overline{ab}$ and $\overline{AB}$ are considered as the algebraic quantities having positive or negative signs.

The amount of rotation, i.e. β , is calculated from the formula

$$a + \beta = \frac{1}{2} \text{arctg} \frac{\overline{AB}}{D} \div \frac{1}{2} \frac{\overline{AB}}{D}.$$

$$\text{i.e. } \beta = \frac{\overline{AB}}{2D} - a.$$

In the example above cited, we have

$$a + \beta = 3.07 \times 10^{-3}; \quad a = 3.25 \times 10^{-3}; \quad \beta = -0.18 \times 10^{-3} \text{ radians.}$$

Here it will be noted that the value of β was generally small and constant relative to that of a , except in some particular cases which could be easily expected. When any small error occurred in the evaluation of a , it caused an enormous discontinuity upon the value of β , so that the error could be easily discovered on tracing the curve of β .

For the second arrangement we have:—In Fig. 10, Pl. II, let the zero-readings be taken when the telescope is in T while the mirrors M_1 and M_3 in the position Mm_1 and the mirrors M_2 and M_4 in the position $M'm_2$. In reality, the reflections of light by the mirrors took place, as a matter of course, in the space of three dimensions; but, for the sake of simplicity, let us assume that the path of the ray of light lies wholly on the plane of the paper. Let ab be the position of the scale, and suppose that a is a point which gives its images in the field of telescope after reflecting at S and S' . Suppose that, after a certain number of operations, the specimen is bent, it is rotated and also the telescope is displaced and rotated relative to the scale. Let their respective values be given by

α =angle through which the mirror M_2 is rotated as the specimen is bent,

$-\alpha$ =angle through which the mirror M_1 is rotated as the specimen is bent,

β =angle through which the specimen is rotated,

δ =the component of the displacement of the telescope parallel to the scale.

Note that the component perpendicular to the scale is negligible relative to the distance between the scale and the telescope.

γ =The amount of rotation of the telescope.

Then, if θ and ω denote the angles between the mirrors M_2 and M_4 , M_1 and M_3 respectively, we have.

TABLE. I.

Specimen convex to	righthand side		lefthand side	
	clockwise	counter clockwise	clockwise	counter clockwise
θ	$\alpha - \beta$	$\alpha + \beta$	$-\alpha + \beta$	$-\alpha - \beta$
ω	$-\alpha - \beta$	$-\alpha + \beta$	$\alpha + \beta$	$\alpha - \beta$

That is to say, provided α and β are taken as algebraic quantities having proper signs, we have

$$\theta = \alpha + \beta$$

$$\omega = \beta - \alpha.$$

Let T' be the last position of the telescope, and put

$R.U.$ = the deviations of the right upper image, which is reflected by the mirrors M_1 and M_2 ,

$R.L.$ = the deviations of the right lower image, which is reflected by the mirrors M_1 and M_4 ,

$L.U.$ = the deviations of the left upper image, which is reflected by the mirrors M_2 and M_4 ,

$L.L.$ = the deviations of the left lower image, which is reflected by the mirrors M_3 and M_4 .

Then, from simple geometry, it may be easily proved that

$$L.L. = \delta + (D + c + d)\gamma,$$

$$L.U. = \delta + (D + c + d)\gamma - 2d\omega,$$

$$R.L. = \delta + (D + c + d)\gamma + 2(c + d)\theta,$$

$$R.U. = \delta + (D + c + d)\gamma - 2d\omega + 2(c + d)\theta.$$

where

$$\overline{ss'} = c, \quad \overline{sa} = d, \quad Ts' = D.$$

If there is no disturbance, evidently we have

$$\beta = 0, \quad \gamma = 0, \quad \delta = 0,$$

So that

$$L.L. = 0.$$

$$L.U. = 2da,$$

$$R.L. = 2(c + d)a,$$

$$R.U. = 2(c + d)a + 2da = 4\left\{d + \frac{c}{2}\right\}a,$$

the last of which is a well known form.

In all cases, we must have a relation between the four values as follows:—

$$L.L. + R.U. = R.L. + L.U.$$

The difference of the two sums indicates an error of observation; whence it gives the means of selecting correct ones from numerous observations. For instance, in the case of a piece of sandstone we have:—

TABLE. II.

<i>M.</i>	<i>R.U.</i>	<i>R.L.</i>	<i>L.U.</i>	<i>L.L.</i>	<i>R.U. + L.L.</i>	<i>R.L. + L.U.</i>	Error.
900 ^{grs.}	1.129	0.529	0.593	-0.004	1.125	1.122	0.003
1200	1.670	0.789	0.877	-0.006	1.664	1.666	-0.002
1500	2.204	1.039	1.159	-0.007	2.197	2.198	-0.001

To calculate the amount of bending, we have four equations containing four unknown quantities. There is, however, one functional relation between the four equations. At the same time, the unknown quantities also may be reduced into three, as δ and γ appear always in one and the same combination.

$$\text{Put} \quad x = L.L.$$

$$x + y = L.U.$$

$$x + z = R.L.$$

$$\text{Then} \quad x + y + z = R.U.$$

Taking any three of the four equations, we may solve them. It is preferable, however, to use all four equations, since none of them is strictly correct. Applying the method of least squares, we have the normal equations

$$4x + 2y + 2z = L.L. + L.U. + R.L. + R.U.$$

$$2x + 2y + z = L.U. + R.U.$$

$$2x + y + 2z = R.L. + R.U.$$

The solution is given by

$$x = \frac{1}{4} \{ 3.L.L. + L.U. + R.L. - R.U. \},$$

$$y = \frac{1}{2} \{ (L.U. + R.U.) - (L.L. + R.L.) \},$$

$$z = \frac{1}{2} \{ (R.L. + R.U.) - (L.L. + L.U.) \},$$

where

$$x = \delta + (c + d + D)\gamma,$$

$$y = -2d\omega,$$

$$z = 2(c + d)\theta,$$

and $\theta = \alpha + \beta$
 $\omega = \beta - \alpha.$

Eliminating x, y, z, θ and ω from the above equations, we have

$$\alpha = \frac{1}{8} \frac{c+2d}{d(c+d)} \left\{ (R.U. - L.L.) + (L.U. - R.L.) \frac{c}{c+2d} \right\}$$

$$\beta = \frac{1}{8} \frac{c+2d}{d(c+d)} \left\{ (R.L. - L.U.) + (L.L. - R.U.) \frac{c}{c+2d} \right\}$$

In the case lately cited, we have

TABLE. III.

$c=12.4 \text{ cm.}, \quad d=241.5 \text{ cm.}, \quad \frac{c}{c+2d} = 2.503 \times 10^{-2}, \quad \frac{1}{8} \frac{c+2d}{d(c+d)} = 1.0099 \times 10^{-3}$				
M	$R.U. - L.L.$	$R.L. - L.U.$	α	β
900 grams.	1.133 cm.	-0.064 cm.	$11.46 \times 10^{-4} \text{ rad.}$	$-0.93 \times 10^{-4} \text{ rad.}$
1200	1.676	-0.088	16.95	-1.31
1500	2.211	-0.120	22.36	-1.76

It is to be noticed that in the above calculation, tangent and arc of an angle are taken to be equal to each other. The greatest angle to be dealt with, indeed, is $\gamma + 2\theta - 2\omega$ which is of an order of 10^{-2} radian: whence the difference between the tangent and the arc is of an order 10^{-6} ; that is to say, it is of an order of 10^{-4} of their own amounts, which is within the error of observation.

The relation between the modulus of elasticity and the amount of bending is given by the well known formula

$$E = \frac{3}{4} \frac{Mgl^3}{ab^3\alpha}$$

where a and b are the breadth and thickness of the specimen, while l is the distance between the corresponding fulcrums.

5. Preliminary Experiments.

The last investigation* with regard to the modulus of rigidity proved a great deviation from Hooke's law even in the case of the

* Loc. cited.

smallest strain. Preliminary experiments showed it to be alike also in the case of bending. Fig. 11 in Pl. II, shows the result of observation on a piece of micaschist, No. 42. The ordinate represents the amount of diviation of the image in the first arrangement, while the abscissae represents the corresponding effective mass in grams. It is clear at a glance that there is a great amount of residual bending when the force becomes nil, and also that the residual vanishes very rapidly when an oppositely directed force is applied. Such is always the case in magnetic hysteresis, especially at heigh temperatures,* and no one would doubt the result.

Examinnig more accurately, however, it was proved that the latter fact was false. The deviation above stated was not due to the bending of the specimen, but also to its rotation. Evaluating these quantities separately in the manner above given, we have the results given in Fig. 12 and Fig. 13 in the same plate. Fig. 12 can be taken as the hysteresis curve in the relation between the bending and the force, while Fig. 13 gives the amount of rotation of the specimen during a cycle. When a series of observation, is completed within one or two hours, rotation of the specimen is the only correction required, so that the first arrangement is sufficient to be relied upon. As the experiment, however, is to be continued during several hours or even for days, it is safer to use the second arrangement.

Influence of the Resisting Mass:—To get rid of the influence of friction, etc, the resisting mass is kept constant during the whole experiment. Now it may be doubted that, as the resisting mass increases with the total mass to be moved, it might have some influence uppon the hysteresis curve. To examine this point, a series of experiments was made on a piece of sandstone, No. 3. The resisting mass was 1000, 1300, 1600, 1900 grams in each successive experiment respectively, while all other conditions remained the same through the four experiments. During the experiment, 1^h50^m—5^h45^m P.M., 19th

* D.K. Morris. On the Magnetic properties and Electrical Resistance of Iron as dependent upon Temperature. Phil. Mag. Vol. 44. 1897.

March 1903, the temperature of the room changed from $12^{\circ}8$ to $12^{\circ}2$, whose influence upon the elasticity may be neglected as we shall see soon after. To get rid of any influence of its initial state, the result was adapted after two complete cycles in each experiment. In Pl. III., the curves in Fig. 14 show the relations between the amount of bending and the corresponding effective mass for successive experiments. The curves in Fig. 15 show the variation of the modulus of elasticity due to the change of bending force during one complete cycle on the above experiments.

It may be necessary to write a remark on the meaning of the term "Modulus of Elasticity." As there is a great amount of hysteresis in the relation of stress to strain, the ordinary conception of the modulus of elasticity is necessarily vague and uncertain. The actual resistance to the deformation in any state whatever, be it already bent or twisted, elastic or plastic at that state, will be taken as the measure of elasticity at that state. Hence, in the above example, the modulus is measured, step by step, by the increase of bending per 200 grams increase of the effective mass. In each curve of Fig. 15, the right and left branches correspond to the cases where the specimen was bent convex towards righthand or lefthand side respectively, while the lower branches correspond to the increasing stress and the upper to the decreasing one. Comparing the curves in these figures, we may safely conclude that the presence of the resisting mass has no sensible influence, or, if any, it is negligibly small.

6. Yielding and Recovery from the Yielding.

The phenomenon of yielding, though it is not so enormous as in the case of torsion, is still sufficiently great to be dealt with. A piece of sandstone, No. 3₁, was loaded with $M_0 = 3300$, $M = 3000$ grams at 4^h27^m P.M. 9th. Feb. 1903.

At the instant of loading we had $\alpha = 27.95 \times 10^{-1}$ for the amount of bending which increased to $\alpha = 33.86 \times 10^{-1}$ at 8^h6^m P.M. and to $\alpha =$

60.57×10^{-4} at 8^h33^m of the next morning. Further observation was continued during about two weeks till the yielding, though it was steadily increasing, was much obliterated by the influence of the temperature-change. The amount of yielding since 3^h30^m P.M. 10th is given in the following table.*

TABLE. IV.

Specimen No. 3₄. Sandstone. Loaded at 4^h27^m P.M. 9th Feb. 1903. $M=3000$ grs., $M_0=3300$ grs.

Total amount of bending $\alpha = \alpha_0 + \alpha_1 + \alpha_2$, where $\alpha_0 = 27.95 \times 10^{-4}$, $\alpha_1 = 32.62 \times 10^{-4} + x$, in radian.

Time 10 th P.M.	Temperature.	α_2	Time 11 th A.M.	Temperature.	α_2
3 ^h 30 ^m	12.0	0.00×10^{-4} rad.	11 ^h 53 ^m P.M.	10.2	10.25×10^{-4} rad.
3 51	11.3	0.02	0 48	10.1	10.43
4 10	10.8	0.15	1 14	10.1	10.54
4 35	10.0	0.25	1 40	10.6	10.53
5 6	9.5	0.58	2 5	11.5	10.85
6 19	9.2	1.44	2 30	11.9	11.69
6 39	9.1	1.82	2 54	12.1	13.55
7 5	9.3	2.17	3 14	12.2	14.99
7 31	9.2	2.38	3 34	12.3	16.87
7 58	9.0	2.52	3 52	12.4	18.41
8 24	9.0	3.19	4 13	12.4	20.31
8 45	8.8	3.26	4 40	12.1	22.66
9 12	8.8	3.52	5 1	11.7	23.86
9 35	8.7	3.70	5 21	11.5	24.44
9 47	8.6	3.96	6 10	11.4	25.53
11 th A.M.					
8 25	6.4	8.79	6 28	11.5	25.83
8 47	6.7	9.07	6 52	11.5	26.04
9 10	7.0	9.31	7 16	11.4	26.25
9 30	7.3	9.29	7 37	11.3	26.50
9 52	7.9	9.52	7 56	11.0	26.70
10 14	8.1	9.77	8 24	11.0	26.85
10 42	8.7	9.91	8 41	10.8	26.91
11 0	8.9	9.91	9 6	10.7	26.96
11 28	9.6	10.11	etc. etc.	etc.	etc.

* On noon of this day, the telescope was slightly disturbed so that the total sum of the yielding could not be known. After this event, I devised the second arrangement.

It will be seen that the amount of bending increased, in a course of two and half days, to, at least, more than three times of its initial amount. The above result as well as the further yielding of the same specimen are plotted on Pl. IV. Even after some tenth of thousands of minutes, steady increase of bending could be seen. It is, indeed, questionable whether there is any limit to the yielding or not. One instance where a plate of marble, resting horizontally on four posts at the corners, in a course of about half a century, was considerably bent by its own weight, is reported by T. J. J. See.* Here it may be remarked that, in Fig. 17, there is an abnormal increase of bending. Close examination showed that it was the effect of temperature-rise, as we shall see in the next section.

Recovery from the yielding:—It is of no small interest to examine whether the yielding above stated is elastic or permanent. From an investigation by F. D. Adams and J. T. Nicolson,† it is evident that even such a comparatively rigid rock as marble may become wholly plastic under suitable condition. In that case, an enormous change of shape occurred in a comparatively short time and it seemed to be permanent. For instance, the diameter of a cylinder increased by 1.388 times of its initial, bulging out by endpressure in only 18 minutes. The structure of the marble deformed in 64 days was essentially the same in character as that which was deformed to the same extent in 10 minutes. The folding of rocks and other kindered phenomena pertaining to the manifold change of shape in rocks are found in great abundance. It is never out of question whether Such phenomena had occurred in a short time under wholly plastic condition and now is in permanent set, or they are the results of yielding, progressing from time to time, wrought by the continuous action of stress, and always ready to recover from their over-strained state.

* The secular bending of a marble slab under its own weight. *Nature*, Nov. 20, 1902.

† An experimental investigation into the flow of marble. *Phil. Trans. of the R. S. A.* Vol. 195, 1901.

If the latter were the case, it would not be wholly unconceivable that an overstrained portion of the earth's crust recovers gradually after its stress have been removed by some geological disturbance. Then, this phenomenon of recovery may be, to be sure, one of the causes of after-shocks of an earthquake, since ultimate result of this phenomenon must be equal that which may be produced by an oppositely directed stress.

A piece of sandstone No. 3, remained loaded, $M=3000$, $M_0=3300$ grams, since 4^h27^m P.M. 9th Feb. 1903 till 7^h50^m P.M. 23rd of the same month, during 14d 3h 23m i.e. 20363 minutes. Then it was unloaded, $M=0$, $M_0=3300$ grams, and the amount of residual bending was observed from instant to instant. As in the case of torsion, it recovered gradually and incessantly. The result of the experiment is given in the following table.

TABLE. V.

Specimen No. 3. Sandstone.

Loaded at 4^h27^m P.M. 9th Feb. $M=3000$ grs. $M_0=3300$ grs.

Unloaded at 7^h 50^m P.M. 23rd Feb. $M=0$ „ $M_0=3300$ grs.

Amount of residual bending= $x-a$; a =amount of recovery.

Time.	a	Time.	a
23 rd P.M. 7 ^h 51 ^m	20.87 $\times 10^{-4}$ rad.	24 th P.M. 1 ^h 34 ^m	27.50 $\times 10^{-4}$ rad.
52	21.59	2 37	28.06
55	21.87	3 15	28.30
57	22.02	4 33	29.06
8 0	22.30	5 34	29.28
4	22.51	6 43	31.09
6	22.37	7 14	31.27
9	22.59	8 18	31.47
17	22.69	9 41	31.84
24	22.95	25 th A.M. 10 0	34.44
57	23.32	P.M. 6 42	37.63
9 35	24.52	27 th A.M. 8 12	45.27
24 th A.M. 8 3	25.91	P.M. 5 28	47.38

Thus, the amount of recovery became increased, in a course of about four days, by more than twice its initial value. The result is also shown in Figs. 18 and 19, Pl. IV.

Effect of recovery on cycles is to be seen from Fig. 20 in Pl. V. Another piece of sandstone, No. 4₃, was loaded with $M=3000$, $M_0=3300$ grams during 2647 minutes. Then it was released gradually from the load and treated in a cyclical manner as usual. The result is given in the following table:—

TABLE. VI.

Specimen No. 4₃. Sandstone.
Loaded with $M=3000$, $M_0=3300$ grams-weight,
from 6^h 35^m P.M. 20th May, 1903.
to 2^h 42^m P.M. 22nd of the same month:
then it is unloaded and loaded cyclically.

M , in grams weight.	First cycle, a in radians.	Second cycle, a in radians.	Third cycle, a in radians.
3000	24.21×10^{-4}	19.12×10^{-4}	17.90×10^{-4}
2700	23.80	18.59	17.51
2400	23.24	18.14	17.08
2100	22.47	17.51	16.50
1800	21.59	16.54	15.72
1500	20.36	15.66	14.71
1200	18.97	14.50	13.50
900	17.25	13.25	12.22
600	15.52	11.59	10.65
300	13.50	9.96	9.02
000	11.31	7.83	7.07
—300	9.02	5.51	4.92
—600	6.68	3.41	2.59
—900	4.29	1.90	0.64
—1200	1.84	—0.62	—1.13
—1500	—0.70	—2.68	—3.42
—1800	—3.12	—5.03	—5.49
—2100	—5.38	—7.60	—7.78
—2400	—9.33	—9.62	—9.69
—2700	—11.17	—11.62	—11.86
—3000	—13.47	—13.86	—13.81
—2700	—13.04	—13.28	—13.15
—2400	—12.46	—12.82	—12.60
—2100	—11.83	—12.20	—11.97
—1800	—11.10	—11.35	—11.30
—1500	—	—10.70	—10.60
—1200	—8.95	—9.64	—9.31
—900	—7.55	—8.01	—7.99
—600	—6.02	—6.50	—6.57
—300	—3.95	—4.33	—4.61
000	—2.02	—2.57	—2.56
300	0.03	0.28	—0.70
600	2.11	1.40	1.32
900	4.18	3.54	3.42
1200	6.19	5.45	5.38
1500	8.26	7.51	7.33
1800	10.57	9.72	9.45
2100	12.54	11.81	11.47
2400	14.75	13.99	13.46
2700	16.93	15.82	15.35

The result is also shown in Fig. 20, Pl. V.

As a natural consequence of yielding and recovery, a piece of rock under over-strain is not indifferent of the direction of the second stress to be applied, even after the piece has long been in the strained condition. For instance, a piece of sandstone, No. 3₄, was subjected to a force due to $M = -1500$, $M_0 = 3300$ grams during 1641 minutes and then a second force was applied in the same direction as the first one. In the next place, the same piece, was acted by the same force during 1234 minutes and then a second force was applied in the opposite direction as the first one. The changes of flexure for equal change of force were very different in these two cases, as shown in the following table:—

TABLE. VII.

$M = M_1 + M_2$. Subjected under $M_1 = -1500$ grams during 1641 minutes.		Subjected under $M_1 = -1500$ grams during 1234 minutes.		Started from neutral state: i.e. $M_1 = 0$.	
M_2	α	M_2	α	M_2	α
-300	-2.00×10^{-4}	300	0.59×10^{-4}	300	2.58×10^{-4}
-600	-4.29	600	2.25	600	6.43
-900	-7.48	900	4.39	900	11.46
-1200	-11.17	1200	6.25	1200	16.95
-1500	-15.06	1500	11.20	1500	22.36
etc.	etc.	etc.	etc.	etc.	etc.

The result is also shown in Fig. 21, Pl. V.

7. Effect of Temperature.

The curve of yielding given in Fig. 17, Pl. IV, as it was noted in the last section, is very irregular, increasing with abnormal rapidity in some moments. Comparing this with the curve of temperature-change during the same time, we may perceive at a glance that the disturbance of yielding corresponds to the variation of temperature.

In Pl. VI, Figs. 22-25, the temperature and the amount of bending are plotted against the laps of time respectively. In Fig. 22, there is an abrupt increase of bending between 46th and 49th hours. In the corresponding part, we notice the rise of temperature. There is, of course, more or less time-lag on the part of yielding, since a piece of rock requires more time to get on the same temperature as the surrounding air than a mercury thermometer.

Here it must be remarked that the rise of temperature is never an ultimate cause of the increase of bending. It is neither more nor less than an inducer. The amount of increase of bending induced by a rise of temperature depends wholly on the capability to yield at that instant. When the capability is large, an enormous increase of bending takes place induced by a little rise of temperature. Looking on the figures, for instance, we see that the rise of temperature was more rapid during 64th---70th hours, while the amount of yielding during the same time was comparatively small.

In so far as the temperature-rise is a mere inducer, the resulting flexure must be irreversible. The flexure, however, decreased a little during 71th hour, when the temperature descended with great rapidity. The above shows that one part of the flexure is reversible with regard to the change of temperature. Whence we must conclude that the effect of temperature is double: firstly, it acts as an inducer,—i.e. it facilitates the flexure-change caused by other agent; secondly, it is one of the ultimate causes of the flexure-change. For the first part, there can be no numerical relation between the variations of both flexure and temperature. For the second part, however, a functional relation must exist connecting the two variations. These two effects always appears hand in hand. When the capability to yield is large, the second part must be obliterated by the first one. After a long time, as the capability to yield tend to vanish, the second part becomes the principal one. This was really the case with the present experiments, as we shall see in the annexed figures in Pl. VI.

In Figs. 23-25, the corresponding curves are similar to each

other, with an exception to be explained in the following lines. Left parts of the two curves in Fig. 23 and right parts of those in Fig. 25 are not parallel; on the contrary, they converge towards the right. Examining them more minutely, we perceive that this abnormality takes place, when and only when the temperature is lower than a definite degree Ca. 9°C . When the temperature is higher than this, the two curves proceed parallel to each other; in other case they are symmetrical to each other. That is to say, the amount of bending increases with the rise of temperature in the first case, but it decreases in the second case, and vice versa.

The above fact is also contained implicitly in the curve of bending in Fig. 22. From 40th to 48th hour, the temperature rose with great rapidity, but the abrupt increase of bending took place only after 46th hour, which indirectly shows that, during 40th–46th hour, as the temperature was below the neutral point, the rise of temperature, on the contrary, diminished the yielding.

The relation between temperature and bending is given more clearly in Fig. 26 of the same plate. The curve has a neutral point in the neighbourhood of Ca. 9°C . That is to say, the elasticity of sandstone is maximum at that temperature in so far the change due to temperature-variation is concerned. In the case of the rigidity-modulus, we had a result strictly analogous to this effect.

To determine any general relation between elasticity and temperature requires further investigation by a special arrangement. Here it is sufficient to remark only that though the change of flexure due to the variation of temperature is unexpectedly great, yet it is almost negligible as compared with the total amount of flexure. Indeed, the increase of bending per degree of temperature-rise in the case of sandstone is of an order 10^{-3} of its total amount.

8. Hysteresis Curve.

Looking on the curve in Fig. 12, Pl. II, we see that there is a tendency on the part of the rock to persist in any strained state

which it may have acquired, especially when the variation of the stress changes its sign. The curve is closed and it is also of simple and regular form, though its path during the increase of stress differs entirely from that during the decrease. A more close examination will prove that the on-curve, when it is turned through two right angles, becomes coincident with the off-curve. All rocks, in so far as the author has investigated on, have this property in common, though they differ in the curvature of the curves and other minute details. Figs. 27-50, Pls. VII-IX, show the hysteresis curves of several rocks of different kinds.

From what was stated above, it is evident that all these specimens had symmetry on both sides, with the exception of one or two schistose rocks. When a specimen was in a strained state, or when it had a crack or the like, the curve, however, lost its symmetry so that the curve did not close, or else the on-curve could not be brought in coincidence with off-curve.

There is one important fact which deserves to be here mentioned. Although the hysteresis curve is of a definite form and traces one and the same curve when a specimen is bent and unbent many times cyclically, the direction of the elongation of curve does not remain fixed when the amplitude of the cycle (i.e. the greatest amount of stress applied to the specimen during the cycle) is varied. As a general rule, the hysteresis curve becomes more and more vertical when the amplitude of the cycle is further and further increased. Figs. 51-53 fully explain this fact. When the centre of the cycle corresponds to the strained state, Fig. 53, this variation of the direction seemed to be rather rapid.

The amount of hysteresis, which is to be measured by the area enclosed by the curve or by some function of it, is not necessarily greater for the rock having smaller modulus of elasticity. For example, red schalsteine No. 14₁ has smaller modulus of elasticity ($2.39-3.09 \times 10^{11}$) than marble No. 6₃ ($3.24-3.51 \times 10^{11}$), but the former has smaller hysteresis than the latter, as it will be seen from Fig. 31,

Pl. VII. and Fig. 41, Pl. VIII. Generally speaking, however, the amount of hysteresis is least for archæan rocks and increases rapidly for new rocks.

9. Variation of the Modulus of Elasticity During the Cycle.

As it was noted in the former sections, the modulus of elasticity is never constant for a given piece of rock. In the case of sandstone, given in Fig. 15, Pl. III, it is evident that the variation of the modulus obeys one and the same law for both on- and off-curve, in so far as the centre of cycle is at the neutral state of the specimen. That is to say, the curves in Fig. 15 are symmetrical with respect to the axis of ordinate.

Further examples showing how the modulus of elasticity varies during one complete cycle are given in Figs. 54-65, Pls. XI and XII., for several different kinds of rocks. Each kind of rock seems to have its special character. If Hooke's law were to hold good, four branches of each curve would all shrink to a single horizontal straight line. In the case where no hysteresis exists, both the upper and the lower branches would coincide with each other to make a line not necessarily straight.

For all cases of rocks here experimented upon, the upper branch is concave towards the positive axis of the ordinate. As to its character, however, the variety is very abundant; circular, hyperbolic, parabolic, oval, and other curves of higher order of complexity. The left lower branch, indeed, is a continuation of the right upper one, and vice versa. But, in saying circular or parabolic, etc., we assume left upper branch as a continuation of the right upper one, and vice versa. The curvature of the lower branches is turned sometimes upwards and other times downwards. That is to say, one piece of rock, e.g. Fig. 61, chloriteschist No. 26₁, becomes more and more stiff as it is bent further and further, while other piece, e.g. Fig. 62, marble No. 6₃, becomes more and more flexible.

From the above fact, it seems that the procedure of bending had opposite effect on the elasticity of the specimens in the two cases, chloriteschist and marble. This fact, however, may be easily understood from the following explanation. When a piece of rock is bent by an increasing force further and further, there must be a limit as to the amount of strain beyond which it can not go on, or else it breaks down: i.e. The piece firstly becomes more flexible and then, after having reached to a minimum elasticity, it begins to become more and more stiff until it breaks down at last. Hence whether the curve is convex or concave up or down depends wholly upon the ratio of the actual stress to the breaking one. This fact is typically shown by the case of graphiteschist, Fig. 59, Pl. XI.

Though it is not easy to determine any law according to which the modulus of elasticity varies with the phase of the cycle, we may find, as a first approximation, an empirical expression for each specimen. For instance, in the case of sandstone whose experimental result is figuratively given in Fig. 15, Pl. III, we have two parabolic equations expressing the upper and the lower branches respectively. If y and x represent $E \times 10^{-11}$ and the phase respectively, we have

for the upper branch, $y_1 = 0.243 + 0.92 x^2$ with a probable error = ± 0.013 ,

and for the lower branch, $y_2 = 0.243 + 0.043 x^2$ with a probable error = ± 0.004 ,

As a matter of fact, the constant term of y_1 is equal to that of y_2 ; it represents the modulus of elasticity at the state where no external force is acting. These two parabolic expressions are traced in Fig. 66, in Pl. XIII. Assuming this relation between the modulus of elasticity and the phase, we may easily calculate the amount of flexure for the specimen corresponding to any bending force not greater than that due to 1000 grams of weight. The result of calculation is given in Fig. 67, Pl. XIII, which coincide with the observed value within a probable error $\pm 7.5 \times 10^{-6}$ while the amount of bending due to $M=1000$ grams is 1334×10^{-6} .

In the case of a piece of chloriteschist, No. 26, Fig. 61, Pl. XII the upper branch can be represented by an hyperbola

$$\frac{y^2}{(5.75)^2} - \frac{x^2}{(0.35)^2} = 1,$$

$$\text{or } y = \sqrt{33.13 + 122.52x^2} \quad , \quad \text{probable error} = \pm 0.13.$$

For one kind of granite, No. 9, Fig. 54, Pl. XI, on the other hand, the relation is given by an ellipse

$$\frac{(y-10.09)^2}{(6.21)^2} + \frac{x^2}{(0.93)^2} = 1 \quad ,$$

$$\text{or } y = 10.09 - \sqrt{38.56 - 44.4x^2} \quad , \quad \text{probable error} = \pm 0.12.$$

This expression, of course, is applicable only within a certain limit i.e. phase < 0.93 .

In so far as the author experimented upon, the modulus of elasticity of all rocks can be expressed as a simple and definite function of the phase in a cyclical process, provided the specimen is not too near its breaking state.

In the following table, the constant term of the expression for every specimen is given as the modulus of elasticity of several rocks. It corresponds therefore to the value of the modulus of elasticity at the instant when the bending force became zero during the specimen, whose section is about one centimetre square and the distance between the fulcrums is 10 cm., was bent cyclically on both sides by a force varying between those due to $M=3000$ grams weight. The value at any other state under different conditions should be, with all probability, greater than those given in this table.

TABLE. VIII.

No.	Rock.	Locality.	Kind.	Density	Mod. of elasticity.	Mean E.	Velocity of Long. Wave.
ARCHÆAN ROCKS.					×10 ¹¹ (c.g.s.)		Kilom. Second.
31 ₁ .	Quartzschist.	Chichibu.	Metamorphic.	2.67	10.48—7.07	8.78	5.73
46 ₁ .	Quartzschist.	Gumma.	"	2.62	8.41—8.40	8.41	5.67
8 ₁ .	Serpentine.	Chichibu.	Eruptive (altered).	2.72	7.73—7.21	7.47	5.24
40 ₁ .	Micaschist.	Ibaraki.	Metamorphic.	2.54	6.49—5.92	6.21	4.94
18 ₁ .	Chloriteschist.	Chichibu.	"	2.88	8.63—5.39	7.01	4.93
7 ₂ .	Peridotite.	Kuji.	Eruptive (altered).	2.61	6.73—5.83	6.28	4.91
26 ₁ .	Chloriteschist.	Chichibu.	Metamorphic.	2.82	7.03—6.29	6.66	4.86
22 ₁ .	Gabbro.	"	Eruptive.	2.71	6.21—5.57	5.89	4.66
24 ₁ .	Graphiteschist.	"	Metamorphic.	2.59	5.12—4.93	5.03	4.41
23 ₁ .	Graphiteschist.	"	"	2.56	3.69—3.37	3.53	3.71
42 ₂ .	Micaschist.	Ibaraki.	"	2.63	1.29—1.16	1.23	2.16
PALÆOZOIC ROCKS.							
34 ₁ .	Adinoleslate.	Gumma.	Sedimentary.	2.64	10.99—10.23	10.61	6.34
12 ₂ .	Clayslate.	Aumi.	"	2.71	10.71—9.08	9.90	6.14
9 ₁ .	Granite.	Mikage.	Eruptive.	2.54	4.31—3.66	3.99	3.96
21 ₁ .	Limestone.	Chichibu.	Sedimentary (Metamorphosed).	2.64	4.14—3.65	3.90	3.84
6 ₃ .	Marble.	Kuji.	"	2.68	3.51—3.24	3.38	3.55
14 ₁ .	Red Schalestein.	Aumi.	Sedimentary.	2.43	3.09—2.39	2.74	3.36
32 ₁ .	Pyroxenite.	Gumma.	"	2.90	2.96—2.91	2.94	3.18
10 ₂ .	Granite.	Kagawa.	Eruptive.	2.57	2.30—2.10	2.20	2.93
29 ₁ .	Limestone.	Gumma.	Metamorphic.	2.66	2.06—1.92	1.99	2.74
TERTIARY ROCKS.							
35 ₁ .	Sandstone.	Chichibu.	Sedimentary.	2.47	3.55—3.51	3.53	3.78
50.	{ Two Pyroxene Andesite.	Awamori.	?	2.70	4.04—2.38	3.21	3.44
2 ₃ .	Tuff.	Izu.	Sedimentary.	1.90	1.39—1.36	1.38	2.69
5 ₃ .	Rhyolite.	Yechuizen.	Eruptive.	2.40	0.90—0.77	0.84	1.87
4 ₃ .	Sandstone.	Kii.	Sedimentary.	2.25	0.68—0.57	0.63	1.67
3 ₄ .	Sandstone.	Chōshi.	"	2.21	0.34—0.20	0.27	1.11
DILUVIUM ROCKS.							
17 ₂ .	Andesite.	Gumma.	Eruptive.	2.63	4.36—4.31	4.34	4.06
16.	Andesite.	Gumma.	"	2.32	0.68—0.63	0.66	1.69

10. Mean Value of the Modulus of Elasticity During One Cycle.

In the last section we learned that the modulus of elasticity varies, during one cycle according to a definite law. When a piece of rock

is bent by a force and unbent by virtue of its elastic property, it is not, evidently, the modulus of elasticity at any particular state, which determines the vibratory motion of the rock. Modulus of elasticity at all different phases of the vibratory motion equally play their parts in causing the motion. Hence, to know the apparent modulus of elasticity during one complete vibration, we must take mean value of the modulus of elasticity at all different phases.

Let $\bar{E}$ be the mean value, then we have

$$\bar{E} = \int_0^1 y \, dx$$

where y is the modulus of elasticity expressed as a function of the phase x .

If the relation between x and y is parabolic, we have

$$\bar{E} = \int (a + bx^2) \, dx = a + \frac{1}{3}b.$$

For the case where it is hyperbolic, we have

$$\bar{E} = \int \frac{b}{a} \sqrt{a^2 + x^2} \, dx = \frac{b}{2a} \left\{ x \sqrt{a^2 + x^2} + a^2 \log (x + \sqrt{a^2 + x^2}) \right\}.$$

We may assume, with all probability, that the function is a power series

$$y = a_0 + a_1x + a_2x^2 + \dots,$$

Then

$$\bar{E} = \int \sum a_n x^n \, dx = \sum \frac{a_n}{n+1}.$$

For a piece of sandstone, when the maximum bending force during the cycle was equal to that due to $M=3000$ grams, we have

$$\text{for the upper branch, } y_1 = 0.152 + 2.35x^2$$

$$\text{for the lower branch, } y_2 = 0.152 + 0.082x^2.$$

Hence, in this case, we have

$$\bar{E} \times 10^{-11} = \frac{1}{2} \int_0^1 y_1 \, dx + \frac{1}{2} \int_0^1 y_2 \, dx = 0.152 + \frac{1}{6} \{ 2.35 + 0.082 \}$$

$$\text{i.e. } \bar{E} = 0.152 \times 3.67 \times 10^{11}.$$

Thus, the mean value $\bar{E}$ taken for one complete cycle is 3.67 times greater than the value E taken at the state of no bending force.

11. Diminution of the Modulus of Elasticity Due to Increase of the Amplitude of Cycle.

As it was lately noted, the hysteresis curve becomes more and more vertical when the amplitude of cycle is further and further increased. This fact expresses that the mean elasticity gradually weakens as the amplitude of cycle increases. The variation of the modulus of elasticity in each cycle given in Fig. 52, Pl. X. is shown in Fig. 68, Pl. XII. At a glance, we see that the greater the amplitude, the lower the curve. In Fig. 69, Pl. XIII, the same result is shown in a somewhat different manner. The modulus is expressed as a function of the phase in the cycle. It will be seen that the modulus of elasticity corresponding to one and the same phase of the cycle is generally greater when the amplitude is smaller.

In this case, also, the curves can all be represented by a series of parabolic expressions. The constant terms of them are, of course, not equal to each other: i.e. they are

TABLE IX.

Amp. (i.e. $\mathfrak{M}$ in grams.)	300	600	1200	1800	2400	3000
E . (c.g.s. $\times 10^{11}$)	0.65	0.46	0.33	0.27	0.21	0.15

This relation between the amplitude of cycle and the modulus of elasticity is also shown in Fig. 70, Pl. XII. Thus, it is very important to notice how the modulus of elasticity diminishes when the amplitude of the cycle increases.

12. Increase of the Modulus of Elasticity due to the Strained State of the Specimen.

In the case of the modulus of rigidity, it was noted that the modulus is comparatively greater in a strained than in the neutral state. This is also the case for the modulus of elasticity. Here it

will suffice to give one example. Firstly, a piece of sandstone No. 4, was applied with a force increasing by $\Delta M=300$ grams step by step. Secondly, the same specimen, after having been under a constant force $M=-3000$ grams during 4027 minutes, was applied, also, with a force increasing by $\Delta M=300$ grams step by step. The modulus in each step is given in the annexed table, and also it is graphically shown in Fig. 71, Pl. XIII.

TABLE X.

Second force: M . in grams.		300	600	900	1200	1500	1800	2100	2400	2700	3000
E . { <i>c.g.s.</i> } $\times 10^{11}$	From neutral state: $F_0=0$.	1.104	1.168	0.810	0.727	0.664	0.578	0.601	0.565	0.517	0.540
	From strained state: $F_0=3000$	2.962	2.169	1.577	1.380	0.987	0.874	0.706	0.702	0.601	0.555

This example will fully express how the modulus of elasticity in a strained state is greater than that in its neutral state.

13. The Velocities of Propagation of Seismic Waves.

In the author's publications above cited it was experimentally as well as theoretically explained that, in the case of distorsional waves, the velocity of propagation is a function of the amplitude of the wave as there exist more or less yielding in the rocks through which the waves propagate, and also that, in view of this inference, we do not see the necessity to assume the path of the tremors to be different from that of the principal shocks. The present experiment relating to other modulus of elasticity, i.e. Young's modulus, gives, it seems to me, more strong foundation to support the above view.

In so far as the above-mentioned experiments can be confidentially relied upon, the following inference may safely be drawn from them, provided we agree that the velocity of wave varies as the square root of the elastic constant of the medium through which the wave propagates.

In § 10, it was noted that the elastic constant varies during one cycle of bending and that all values at different phases of the cycle equally play their parts in causing the motion, i.e. the apparent value of the elastic constant during one complete vibration must be the mean value of all the values at different phases. Now the elastic constant which determines the velocity of wave is, as a matter of course, not its value at any particular phase, but its mean value taken for one complete cycle.

Assuming $y = a_0 + a_1x + a_2x^2 + \dots$

we have $\mathfrak{E} = \int_0^1 \sum a_n x^n dx = \sum \frac{a_n}{n+1}$

In usual case, what is given as the value of the elastic constant is

$$E = a_0 + a_1 f(x_1)$$

where x_1 is a certain small quantity particular to the mode of experiment.

In Table VIII, the value of a_0 is given as the value of the modulus of elasticity; accordingly the value of velocity there given is calculated by the formula

$$v = \sqrt{\frac{a_0}{\rho}}$$

It will be noted that these values, as a matter of course, are generally smaller than those given by Professor H. Nagaoka in his valuable

report:* $V = \sqrt{\frac{E}{\rho}}$

In the actual case, what determines the velocity, is neither v nor V , but, with all probability, it should be given by

$$\mathfrak{V} = \sqrt{\frac{\mathfrak{E}}{\rho}}$$

Since the mean elasticity $\mathfrak{E}$ is remarkably greater than the values a_0 or E , the actual velocity of propagation $\mathfrak{V}$ must be somewhat greater than those v or V given in the tables. For instance, in the case of

* H. Nagaoka. Elastic Constant of Rocks and the Velocity of the Seismic Waves. This Publication No. 4. 1900.

a piece of sandstone, the result of experiment showed that the mean value $\mathfrak{G}$ is 3.67 times greater than the constant term a_n . Whence, we must have

$$\frac{\mathfrak{G}}{v} = \sqrt{3.67} = 1.92,$$

that is to say, the actual velocity would be probably twice the value given in the table. In general, the actual velocity would be

$\sqrt{\left\{ \sum \frac{a_n}{n+1} / a_0 \right\}}$ times greater than that given in the table.

14. Diminution of the Velocity due to Increase of Amplitude.

The velocity must necessarily diminish with increase of the amplitude of the wave, since the elastic constant diminishes in that case as fully explained in the eleventh section. From the instance given in that page we have a good example to show how the velocity changes with the amplitude.

TABLE XI.

Ratio of Amplitudes.	1	2	1	6	8	10
Ratio of Velocities.	2.08	1.75	1.48	1.34	1.18	1.00

This relation between the amplitude and the velocity is more clearly shown in Fig. 72, Pl. V. The velocity increases twice or more while the amplitude diminishes from $\mathfrak{M}=3000$ to $\mathfrak{M}=300$ grams.

Examining the course of the curve, we may safely conclude that any further diminution of the amplitude will give very rapid increase of the velocity.

15. Increase of the Velocity due to the Strained State of Stratum.

As the elastic constant is comparatively greater in the strained

than in the neutral state, the velocity must, as a matter of course, be correspondingly greater in the former state than in the latter. In the example shown in Table X, the ratio of the values of elastic constant for the first step of flexure is 2.962:1.104 so that the ratio of the velocities will be 1.72:1.05 or 1.64. In other words, the velocity in that strained state must be 1.64 times greater than that in the neutral state. This is, of course, nothing but an example; general relation between them, however, would not much deviate in its quality.

16. Diminution of the Velocity due to Increase of Temperature.

Though the variation of the elastic constant due to temperature-rise is comparatively small, it can never be neglected in so far as the velocity of seismic waves is concerned, since the underground temperature rapidly rises with the increase of depth. According to Professor A. Tanakadate,* the underground temperature increases at a rate greater than 25°C per kilometre of depth.

The change of the elastic constant, on the other hand, is Ca. 0.5 % per degree of temperature-change for the case of sandstone. That is to say, the elastic constant diminishes by 12.5 % per kilometre of depth, provided all other conditions remain the same. Then the velocity would proportionally diminish as the depth gradually increases, so that the influence of the underground temperature on the velocity of propagation would be too great to be neglected.

Here a remark may be added on the existence of a stratum of maximum velocity of propagation, proposed by Professor H. Nagaoka. That the modulus of elasticity increases in a greater rate from caenozoic to archaean rocks than the density does, is surely an established fact. When the effect of temperature is taken into account, however, the depth of a stratum where such old rocks abundant can

* A. Tanakadate. The Pub. of the I.E.C. in Japanese Language. No. 45. 1903.

never be put out of consideration, since the increase of depth tends to increase the density but to diminish the elastic constants for one and the same kind of rock, if the elastic constant of rocks with earth's crust behave in the same manner as sandstone as regard temperature. According to geologists,* the thickness of each of quaternary, tertiary and mesozoic rocks is some three or four kilometres, while that of palaeozoic attains twenty five or more kilometres in some regions. The summation of the thickness of the strata of different ages, of course, includes only the part which was revealed to the earth's surface by some geological disturbances. Whence it follows that to attain the main stratum of palaeozoic rocks we must go deep in, at least, some ten kilometres, and for a stratum of archæan rocks, at least, thirty kilometres. The underground temperature, however, at such a great depth must be tolerably high, and the consequence of it would probably in a great diminution of the elastic constants, so that the depth of the stratum of maximum velocity, if it exist at any rate, would be greatly shortened. The author would not, however, insist in this opinion till more accurate observations on the change of the elastic constants due to temperature-rise, which are in course of preparation, will fully elucidate the relation between the elastic constants and the temperature.

17. Note on the Existence of Paths of Maximum Velocity and Seismic Shadow.

Notwithstanding the doubt about existence of a *stratum* of maximum velocity, there may exist, with all probability, several *paths* of maximum velocity of propagation within the earth's crust. As geology teaches us, within the earth's crust there are scattered everywhere veins and dikes of different kinds of old rocks, uplifted by geological disturbances, some of which run over many hundreds or thousands of kilometres.

* Encyclopædia Britannica : Geology.

In this case, it is true, the velocity along such a vein or the like is greater than that through any of the surrounding strata, so that the seismic waves mainly propagate through that region.

As a consequence of the above result, if an observing station be situated on such a vein, not only the number of earthquakes observed at the station is greater than that observed at any of the stations in the neighbourhood, but the direction of motion would not necessarily indicate the position of the seismic centre. It is of daily experience that observers in some districts always feel any earthquakeshock to come from one particular direction even when the seismic centre is in entirely different direction, provided the centre is not too near the observers.

As other consequence, there may exist *seismic shadow*: or, in other words, *seismic waves may be shielded by a vein or dike of old rocks*. As the elastic constants is neither negligibly small nor infinitely great for any rock, the shielding, of course, is not perfect. Strong earthquakes, however, may be reduced to weak ones and weak shocks to insensible tremors. After all, earthquakes originating in one region may always be well observed in the station while those originating in the other region may fail to be observed in the station.

In Professor F. Ōmori's paper* we find the most interesting example to support the above consideration. Of the earthquakes which happened between Sept. 1887 and July 1889 in Central Japan, those whose origins were situated within certain boundaries were always not felt in Tōkyō, though the weaker earthquakes of more distant origins were easily felt.

18. A Hint to the Frequency of After-shocks.

Even at the present day, after all that has been written on earthquakes, but little is really known as to the frequency of after-shocks. An empirical formula,

* F. Ōmori. This Publication. No. 11. 1902.

$$F' = \frac{k}{h+t}$$

in which k and h are constants, was proposed by Professor F. Ōmori * about ten years ago. How his hyperbolic formula gives satisfactory results is sufficiently shown by him in the valuable paper "On the after-shocks of Earthquakes," in which the formula is applied to the three recent great earthquakes in Japan; namely, those of Kumamoto in 1889, of Mino-Owari in 1891, and of Kagoshima in 1893. Lately, other formula, in a form of logarithmic function was obtained by O. Euyā,† founded on three assumptions. A result of labourious calculation is given by him to show that the logarithmic formula is better than the hyperbolic.

To get any reliable formula for the frequency of after-shocks, the first step for it is to know what is the cause of after-shocks. Probably several distinct causes should be recognized, for it is hardly to be supposed that all subterranean disturbances, differing as they do so widely in intensity and in duration, should be referable to one common mechanism. Each succeeding geological disturbance, the fracturing, dislocation, caving-in of ill-supported regions, and also establishment of lines of freedom for the exhibition of volcanic activity which would accompany these changes, would promote the aftershocks.

According to the intrinsic meaning of the name "After-shock," however, the nearest cause must be due to residual disturbance in the geotechnic condition after the primitive-shock has recovered. An earthquake not receiving any participation of this residual is no after-shock, but an independent earthquake. Standing on this principle, with an assumption that the frequency of after-shocks in a given instant is proportional to the rate with which the earthcrust recovers from the residual disturbance, one more general formula for the frequency may be easily obtained. The above assumption is, to say in other words, that if the earthcrust were perfectly elastic, the fre-

* F. Ōmori. The Jour. of the coll. of Science Vol. VII. Tōkyō.

† O. Euyā. The Pub. of the E.I.C. in Japaneses Language. No. 35. 1901.

quency of earthquakes would be proportional to the rate with which the disturbance of the earthcrust would be produced.

From what has been explained in the sixth section we know, as a matter of fact, that a piece of rock yields under a constant action of force, and also that the residual strain surviving the force diminishes from instant to instant, i.e. the rock recovers from its overstrain. This last phenomenon must be the essential cause of the after-shocks. Thus, the first step is to find any formula expressing the rate of recovery, or the rate with which the residual varies with time. One form of such a formula, however, was lately deduced from the logarithmic law of yielding, as it was given in the author's paper above cited. The formula is

$$\rho = k \log \frac{\Gamma(2p+1) [\Gamma(p+t+1)]^2}{[\Gamma(p+1)]^2 \Gamma(2p+t+1) \Gamma(t+1)} \dots\dots\dots (I)$$

where ρ is the total amount of recovery at the instant t , both ρ and t being reckoned from the instant when the external force is wholly withdrawn, while k and p are constants, of which the former specifies the rock and the latter specifies the time-lapse required by the force to attain its maximum.

Let F be the frequency, then the above assumption is

$$F \propto \frac{d\rho}{dt}$$

i.e. if c is a constant, we have

$$\begin{aligned} F &= c \frac{d\rho}{dt} \\ &= ck \log \frac{[p+t+1]^2}{(2p+t+1)(t+1)} \\ &= ck \log \left\{ 1 + \frac{p^2}{(2p+1) + 2(p+1)t + t^2} \right\} \dots\dots\dots (II) \end{aligned}$$

Thus we have a logarithmic form for the frequency of after-shocks. One curve of frequency for some particular values of c , k and p is drawn in Fig. 73, Pl. XIV. A little consideration on the nature of

the constant p will make it reasonable to neglect the term $\frac{t^2}{p^2}$ so long as t is not very large. Then we have, to the first approximation,

$$F = k' \log \left\{ 1 + \frac{1}{A+Bt} \right\} \dots\dots\dots (III)$$

which is the same with that of Enya. Again, expanding the logarithmic function and taking its first term only, we have Professor Ōmori's formula

$$F = \frac{k''}{k+t} \dots\dots\dots (IV)$$

Though the resulting formula for the frequency are tolerably well found in so far as they were tested by Professor Ōmori and Mr. Enya, the original formula (I) for the recovery is not wholly out of question. The assumptions under which the formula (I) is deduced are very far from being the case in an earthquake. The force acting on rock is assumed to increase intermittently, and, to be worse, it is assumed to be withdrawn not suddenly but slowly and intermittently. The following may be more close to the actual case.

Whatever may be the real cause of an earthquake, it is reasonable to consider the force as increasing constantly with time, i.e.

$$df = k dt$$

where k is a constant, and attaining a sufficient amount F to cause an earthquake at time T , so that we have

$$F = k T.$$

Suppose the logarithmic law of yielding, which was empirically established in the last series of experiments, to be granted, so that

$$d\eta = K df \log (t + \tau),$$

where η is the amount of yielding and K a constant specifying the kind of rock while τ is a constant referring to the choice of origin of time t . Then we have

$$\eta = K k \int_0^T \log (t + \tau) dt$$

$$= k K (T + \tau) \log \frac{T + \tau}{e} + k K.$$

If the total force F is suddenly withdrawn at the instant $t = T$, it may be easily proved that the residual strain at any instant $t = T + t'$ is given by

$$\sigma = k K (T + t' + \tau) \log \left\{ \frac{T + t' + \tau}{t' + \tau} \right\}.$$

Now, as the frequency is assumed to be proportional to the rate of recovery, we have

$$\begin{aligned} F &= -c \frac{d\sigma}{dt} \\ &= \frac{c.k.K.T}{t + \tau} - c.k.K \log \left\{ 1 + \frac{T}{t + \tau} \right\}, \end{aligned}$$

where τ, c, k, K and T are all constants, and t is written for t' whose origin may be any instant, provided proper value is given to the constant τ .

Here the frequency F may be considered to be composed of two terms F_1 which is hyperbolic and F_2 which is logarithmic, so that h being a constant

$$\begin{aligned} F_1 &= \frac{h}{t + \tau}, \\ F_2 &= \frac{h}{T} \log \left\{ 1 + \frac{T}{t + \tau} \right\}. \end{aligned}$$

As the constant T is, with all probability, very great compared to other constants c, k and K , the main term is the first one, so that the curve of frequency F is a little different from a hyperbola.

When h is given, the curve of F_1 takes a definite form, but the curve of F_2 is wholly indefinite in so far as T , i.e. the time required by the force to attain its greatest amount, is not given. That is to say, if the time during which the causal agent of the earthquake existed is long, the curve of frequency approaches the hyperbola represented by F_1 , but it deviates more and more from the latter curve as the duration T becomes shorter and shorter. Since F_2 generally increases as T decreases, the number of after-shocks of an earthquake

of rapid generation is necessarily smaller than that of other earthquake of gentle generation, in so far as the other conditions required to cause the earthquakes remain constant. Numerical example given below will show it more clearly.

TABLE. XII.

$h = 1000; \tau = 1.$		F_2		F	
t	F_1	$T = 100$	$T = 1000$	$T = 100$	$T = 1000$
1	500	39	6	461	494
2	333	35	6	298	327
3	250	33	6	217	244
4	200	30	5	170	195
5	167	29	5	138	162
6	143	27	5	116	138
7	125	26	5	99	120
8	111	25	5	86	106
9	100	24	5	76	95
10	91	23	5	68	86
11	83	22	4	61	79
12	77	22	4	55	73
13	71	21	4	50	67
14	67	20	4	47	63
15	63	20	4	43	59
16	59	19	4	40	55
17	56	19	4	37	52
18	53	18	4	35	49
19	50	18	4	32	46
20	48	18	4	30	44
21	45	17	4	28	41
22	43	17	4	26	39
23	42	16	4	26	38
24	40	16	4	24	36
25	33	15	4	18	29
32	30	14	3	16	27
39	25	12	3	13	22

The curves of F_1 and F are drawn in Fig. 74, Pl. XIV. In this example, suppose the unit of time to be one month, then the number of after-shocks during the first, second, third, etc. one month would be either 461, 298, 217, etc. or 494, 327, 244, etc. respectively, according as the time required by the force to attain its greatest amount was a hundred or a thousand months.

19. Curves of Iso-frequency of After-shocks.

The discussion in the last section refers to the frequency of after-shocks in the very centre of disturbance, i.e. the seismic focus of the primitive earthquake. It must be borne in mind, however, that such a centre, so far from being anything like a mathematical point, is in nature a subterranean region, which in many cases, is undoubtedly of very large dimensions. Whatever may be the real origin of the after-shocks, it is reasonable to regard them as proceeding from the seismic focus. If the earth were a homogeneous solid, perfectly isotropic, the curves of iso-frequency would take the form of a series of closed curves around the seismic focus. As a matter of fact, however, the earthcrust is made up of rocks varying greatly in physical properties, each having its own density and elasticity. To make the variation more discontinuous, rocks of all geological ages are mingled together, as it were, by a series of geological disturbances, and they are scattered about through the earth crust.

As to the relation between the frequency y at any place, distant R from the seismic focus, and the mean radius r of the curve of iso-frequency, which is assumed to be a circle, corresponding to that place, Professor F. Ōmori proposed an empirical formula

$$y = a b^{-r}$$

where both a and b are constants. Here a hint is given to show how the existence of hysteresis plays a great part in the frequency of after-shocks, i.e. $r \sim R$ increases very rapidly as there exist different amounts of hysteresis in the stratum of rocks forming the path of the seismic wave.

From the figures in Pls. VII and VIII, it will be easily seen that, as a general rule, the amount of hysteresis decreases with an increases of the modulus of elasticity. Though nothing can be said about any numerical relation between hysteresis and elasticity, but in the rocks so far examined, certain relation between these two physical constants seems to exist. Thus it would not be a wild conjecture to

say that the amount of hysteresis gradually diminishes from cainozoic, e.g. sandstone and rhyolite, to archæan rocks, e.g. peridotite and quartzschist, in a definite, though not yet known, ratio.

It is a matter of course that a seismic wave propagating through a medium of greater hysteresis fades more rapidly than that propagating through other medium of less hysteresis. The consequence is that, provided the frequency of after-shocks at the seismic focus is given, the frequency at any place having a given distance from the seismic focus increases with the geological age of rocks forming the path of wave between the focus and the place. That is to say, the distance between two successive lines of iso-frequency is greatest where archæan rocks lie and becomes less and less through palæozoic and mesozoic rocks to reach its least value at the region where cainozoic rocks extend.

Now examining the curves of iso-frequency in the great Japanese earthquakes carefully drawn by Professor F. Ōmori in his paper above cited as well as many others, it is clearly seen that the irregularities of the curves conforms with that of the geological distribution of rocks in those regions. For example, in the case of Mino-Owari earthquake, in which the total number of after-shocks during one year, 1892, amounted to more than eight hundreds, four curves of iso-frequency are shown, with corresponding geological distribution of rocks, in Fig. 75, Pl. XIV. The iso-frequency curve of $F=500$ lies wholly within quaternary rocks and is in an elongated form extending nearly north and south between Gifu and Nagoya. The central region of the after-shocks may be in a similar form. The succeeding curves of iso-frequency, however, so far from being similar to the first, are in quadrantal forms. In the western part, indeed, where the curves lie within quaternary rocks, they are all parallel to each other; but in other three directions they shrink in or swell out with all possible irregularities. These irregularities, however, turn to a regularity when the geological distribution of rocks in the corresponding regions is taken into account. To express in a simple terseness, *it swells out where palæozoic or better archæan*

rocks predominate and shrinks in where caenozoic rocks extend. This simple law is sufficiently satisfied up to very minute portions, as the figure proves it most clearly.

gh 7
An inference to be drawn from the above is that the conductivity of seismic wave, if we are allowed to employ such a term from some analogies in heat and electricity, is least for caenozoic rocks and, increasing step by step from mesozoic to palaeozoic, it becomes many times greater for archaean rocks. As a corollary, since the geological map indicates only surface distribution of rocks, we may conclude that the seismic wave mainly transmits through the earth's surface, or quite probably, seismic action is mainly due to surface waves discussed by Lord Rayleigh, and recently propounded by Lamb for isotropic medium. Any further discussion, however, as to the seismic wave-conductivity of several rocks requires more precise quantitative investigation of the amount of hysteresis for these rocks.

20. Conclusions.

In so far as the present experiments extend, we have the following conclusions.

1. In most rocks, Hooke's law does not hold even for stress equivalent to a few percentages of their breaking forces.
2. Any rock yields slowly but progressively under a constant force, though the rate of yielding diminishes with the increase of duration. It recovers from the yielding when it is released from the force; but it seems to require an infinite time to return to its initial state by itself.
3. If the modulus of elasticity is proportional to the ratio of the change of force to the change of flexure produced by that force-variation, it is wholly indeterminate, in so far as its previous history as well as its present condition is not completely known.
4. When a piece of rock is bent further and further, the modulus of elasticity firstly diminishes and then, passing through its minimum

value, increases again to a certain amount till the piece is broken. The modulus of elasticity in a virgin piece seems, as a matter of course, to be much greater than that usually obtained by assuming Hooke's law.

5. When a piece of rock is bent right and left cyclically, the modulus of elasticity varies not only from point to point in a cycle, but also from cycle to cycle, provided the amplitude of the cycle does not remain constant. //

6. The mean modulus of elasticity taken for one complete cycle is much greater than the modulus of elasticity estimated in the usual manner.

7. The modulus of elasticity diminishes when the amplitude of the cycle increases, and the variation is more rapid for smaller amplitude than for larger one. This last fact is in contradiction to the assumption that for small amplitude the modulus of elasticity may be considered as a constant.

8. The modulus of elasticity of a piece of rock increases when the piece is already in a strained state.

9. The modulus of elasticity generally increases from caenozoic to archæan rocks. The amount of hysteresis, on the contrary decreases from the new rocks to the old ones.

The inferences to be drawn from the above results, in so far as seismology is concerned, are as follows ;—

7/ 1. The velocity of propagation of seismic wave is least for quaternary rocks and, increasing with age, it becomes greatest for archæan rocks.

2. The velocity, as it is a function of the mean modulus of elasticity taken for one complete vibration, must be much greater than that estimated in the usual manner.

4. The velocity must diminish when the amplitude of seismic wave increases: the rate of diminution is greater when the amplitude is smaller than in the other case.

4. Along some veins or dikes of old rocks running through the

earth's crust, the velocity of propagation is maximum. Consequently, the intensity as well as the direction of seismic motion may be very different for two neighbouring stations. Further consequence results on seismic shadow; i.e. seismic wave may be shielded by a vein of old rocks.

5. Seismic wave-conductivity of rocks is least for cainozoic rocks and, increasing from mesozoic to palæozoic rocks, it becomes many times greater for an archæan rocks. Consequently, the curves of iso-frequency of after-shocks swells out or shrinks in very rapidly according as the region consists of archæan or cainozoic rocks.

6. Actual coincidence of the curves of iso-frequency with the geological distribution of rocks in the region, which is the case, e.g., for Mino-Owari earthquake where the number of after-shocks during one year, 1892, amounts to 867 at its central region, may be explained on the supposition that the seismic waves are mainly transmitted along the earth's surface. It is quite probable that seismic action is mainly due to surface waves discussed by Lord Rayleigh, and recently propounded by Lamb for isotropic medium.

7. As to the frequency of after-shocks at a central region, the frequency F at any time t is given by

$$F = \frac{c.k.K.T}{t+\tau} - c.k.K \log \left\{ 1 + \frac{T}{t+\tau} \right\}$$

where τ, c, k, K and T are constants of different kinds: i.e.

- τ refers to the choice of the origin of time t ,
- c determines the amount of strain required to produce one after-shock,
- k is the force produced in unit time, by accumulation of which the primitive earthquake took place,
- K is a constant specifying the rate of yielding of the rock in the central region,
- T is time required by the accumulating force to attain its greatest amount.

Consequently, other conditions being equal, the frequency of after-

shocks is greater for an earthquake which is slowly generated than for rapidly generated one. The curve of frequency is nearly hyperbolic: its deviation from hyperbola is greater in the latter case than in the former.

REMARKS:—Preliminary experiments with sandstone show that the modulus of elasticity is much affected by the variation of temperature: i.e. ca. 0.5 % per degree. It does not, however, necessarily diminish with an increase of temperature when the temperature is low: i.e. it is maximum at ca. 9°C.

If the above fact be true for most rocks, the velocity of propagation would diminish with the increase of temperature of the medium. Consequently, any cause of the temperature-rise would also be a cause of the velocity-diminution. For instance, as the underground temperature rises very rapidly with the increase of depth, the velocity would diminish proportionally, provided all other conditions remain the same.

In conclusion, I wish to express my great indebtedness to Mr. Fukuchi for valuable informations concerning the geological characters of the specimens. My best thanks are also due to Professor H. Nagaoka, under whose most kind guidance I carried out this experiment.

EXPLANATION OF PLATES.

Pl. I.

- Fig. 1.** Sketch of the modification of König's arrangement.
 „ **2.** Sketch of the first arrangement.
 „ **3.** Sketch of the second arrangement.
 „ **4.** View of the four images visible in the field of telescope.
 „ **5.** Front view of the flexure apparatus.
 „ **6.** Side „ „ „ „ „ „
 „ **7.** Plan of the same.

Pl. II.

- Fig. 8.** A little iron framework by which the bending force is applied to the specimen. W_1 and W_2 are two wedges, of which the former is fixed while the latter is movable. The specimen is tightly clamped between them by the screw S . The bending force is due to the difference of weights suspended at the extremities of the strings S_1 and S_2 .
- Fig. 9 10.** Sketches of the first and second arrangements respectively. These show the geometrical relation between the bending of the specimen and the deviations of the images within the telescope-field.
- Fig. 11.** This shows the result of preliminary observation on a piece of micaschist. The ordinate represents the amount of deviation of the image in first arrangement, while the abscissa represents the corresponding effective mass in grams weight.
- „ **12.** This shows the relation between the amount of bending of the above specimen and the corresponding force applied to the specimens.
- „ **13.** This shows the amount of rotation of the specimen as a whole during one complete cycle of bending in the above experiment.

Pl. III.

Fig. 14. These are the hysteresis curves for bending of a sandstone. The resisting masses are different for the four curves.

„ **15.** These curves show the variation of the modulus of elasticity due to the change of bending force during one complete cycle in the above experiments. In each curve, the right and left branches correspond to the cases where the specimen was bent convex towards righthand or lefthand side respectively, while the lower branches correspond to the increasing stress and the upper to the decreasing one. Comparing these four curves, we may safely conclude that the presence of resisting mass has no sensible influence, or, if any, it is negligibly small.

Pl. IV.

Figs. 16 17. Yielding of sandstone under constant force, $M=3000$, $M_0=3300$ grams. That is to say, the amount of bending of the specimen is plotted against the time during which the specimen was subjected to the constant force.

„ **18 19.** Recovery from the yielding of the above specimen, which was loaded with $M=3000$, $M_0=3300$ grams during 20363 minutes.

Pl. V.

Fig. 20. Effect of recovery from the yielding on cycles. A piece of sandstone, loaded with $M=3000$, $M_0=3300$ grams during 2647 minutes, was treated in cyclical process as usual.

„ **21.** Curve A represents the relation between the amount of bending and the corresponding amount of force acting upon the specimen, which was initially in a natural state. In curves B and C, the specimen was

initially in a strained state; i.e. in curve *B*, the specimen was subjected to $M_1 = -1500$ grams during 1234 minutes, while in curve *C* it was subjected to the same force during 1641 minutes. Comparing these three curves with each other we see that, in the neighbourhood of starting point, of the three curves, *A* is more steep than *C* which is more steep than *B*.

- „ 72. The ordinate represents the velocity of propagation of seismic waves through a stratum of sandstone, while the abscissa represents the amplitude or the maximum stress given to the rock during one complete vibration.

Pl. VI.

Figs. 22-25. In each figure, the upper curve shows the variation of temperature with time, while the lower that of bending, under constant force.

Fig. 26. The amount of bending is plotted against the corresponding temperature.

Pls. VII-IX.

Figs. 27-50. Examples of flexural hysteresis in several rocks of different kinds.

Pl. X.

Fig. 51-53. The curves in these figures show how the hysteresis curve varies when its amplitude is varied.

Pls. XI. and XII.

Figs. 54-65. In each figure, the four branched curve represents the variation of the modulus of elasticity during one complete cycle of bending. Refer to the explanation of Fig. 15.

Pl. XII.

Fig. 68. This shows how the four branched curve changes its form with the amplitude of cycle.

- „ 70. Relation between the modulus of elasticity at the

state of no stress with the maximum amount of stress applied to the specimen during the cycle.

Pl. XIII.

- Fig. 66.** Variation of the modulus of elasticity during one complete cycle, calculated by parabolic formula for sandstone.
- „ **67.** Relation between the amount of bending and the force during one complete cycle, calculated by the above parabolic formula. This is to be compared with the curves in Fig. 14, Pl. III.
- „ **69.** The ordinate represents the modulus of elasticity and the abscissa the ratio of the actual force to the maximum force applied to the specimen during the cycle. The maximum force is 300 grams weight for the upper most curve, and increasing step by step, it is 3000 grams weight for the lowest one.
- „ **71.** Both curves *A* and *B* represent the variation of the modulus of elasticity with the change of the amount of force. Curve *A* starts from the natural state of the specimen, while curve *B* starts from a state where the specimen was subjected under a force $M = -3000$ grams during 2652 minutes.

Pl. XIV.

- Fig. 73.** Curve of frequency of after-shocks of an earthquake calculated by logarithmic formula.
- „ **74.** Curves of frequency of after-shocks. Curve *a*; calculated by hyperbolic formula. Curves *b* and *c*; calculated by the formula deduced from the principle of residual strain.
- „ **75.** Geological map of Mino, Owari and the neighbouring districts, with the iso-frequency curves of after-shocks, during 1892, of the Mino-Owari earthquake in 28 Oct. 1891. The iso-frequency curves are copied from Pro-



Fig. 9.

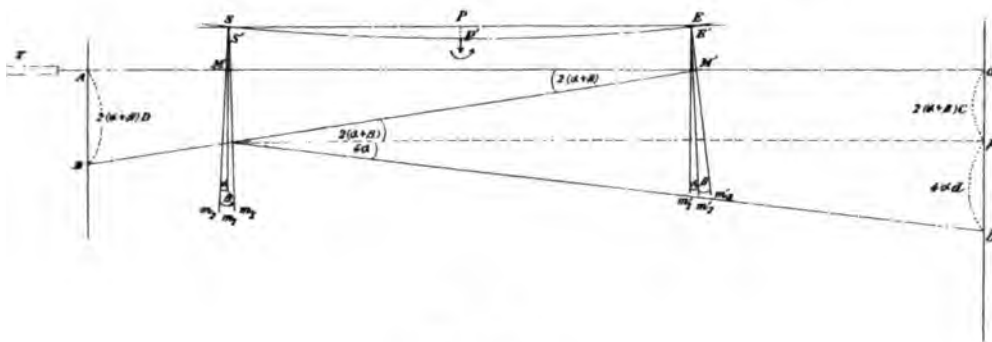
$$\begin{aligned}MM' &= C \\AN' &= D \\MC &= D\end{aligned}$$


Fig.10.

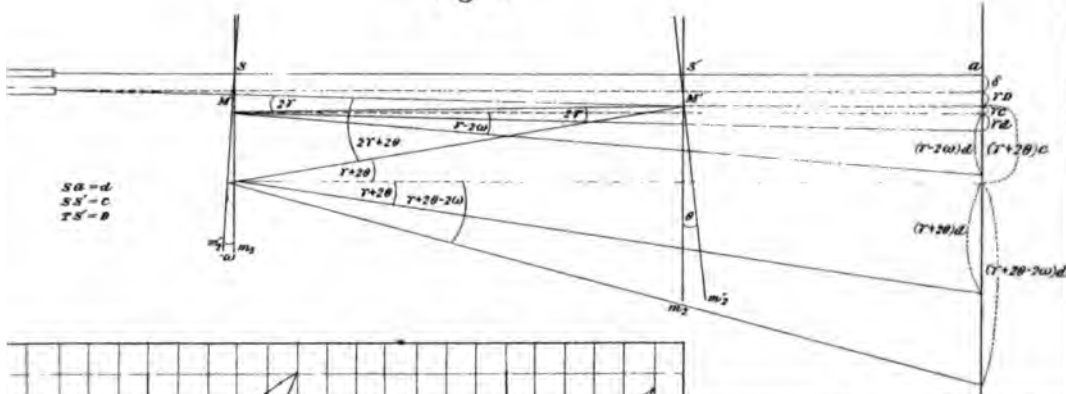


Fig. 8.



Fig.12.

Fig.11.

No. 422.
Micaschist.

Fig.13.

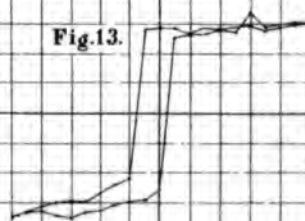


Fig.14.
No. 34.
Sandstone.

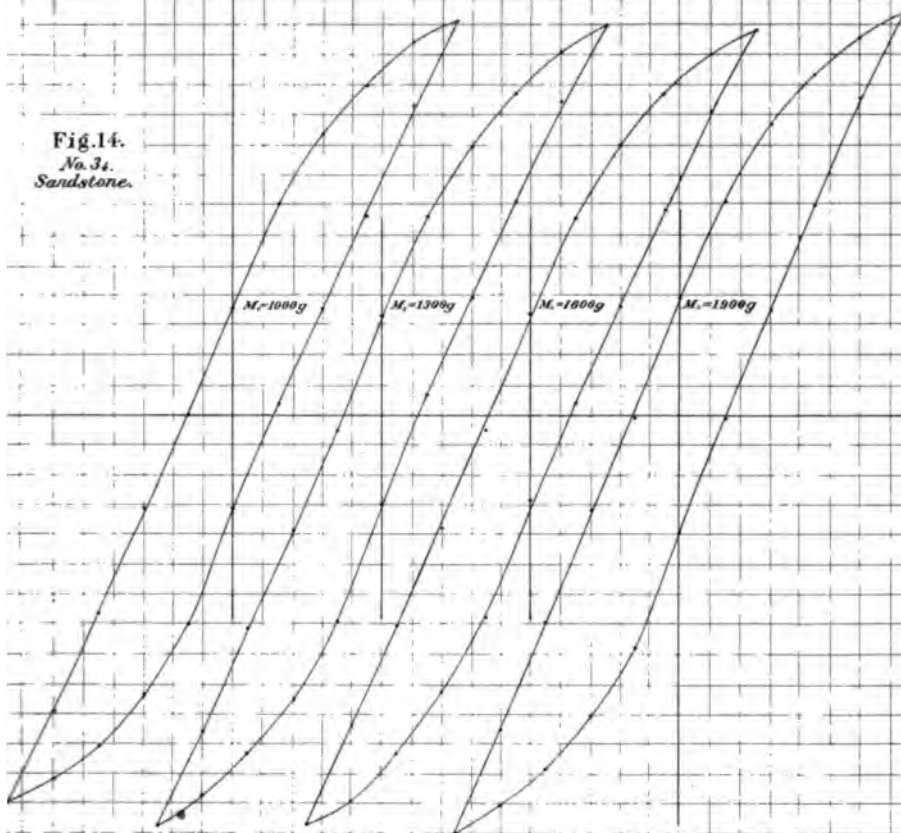


Fig.15.

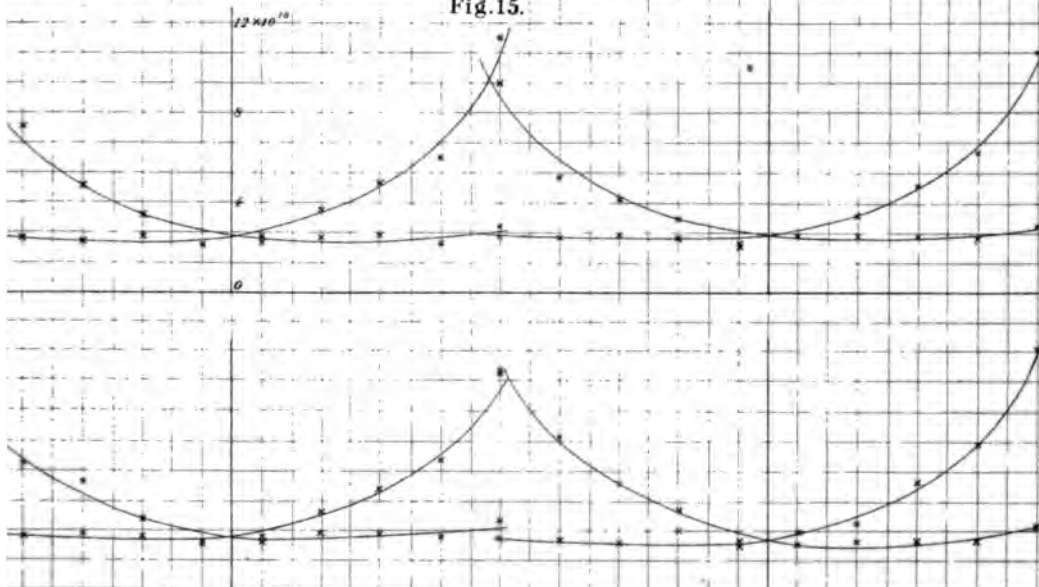


Fig.16.
No. 34.
Sandstone.

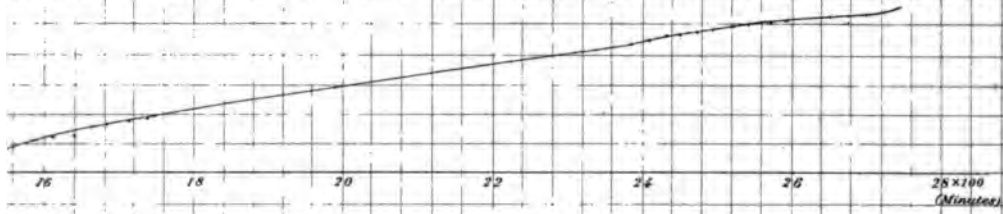


Fig.17.
No. 34.
Sandstone.

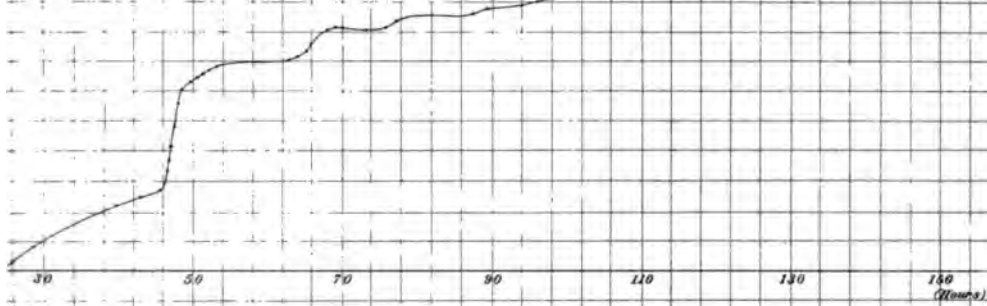


Fig.18.
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Sandstone.

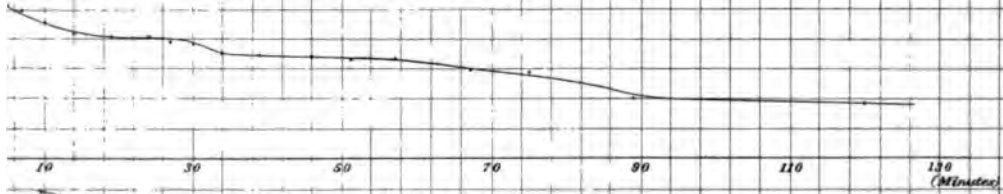
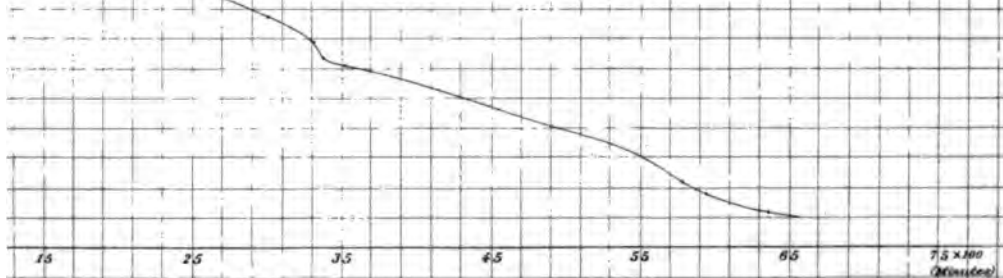
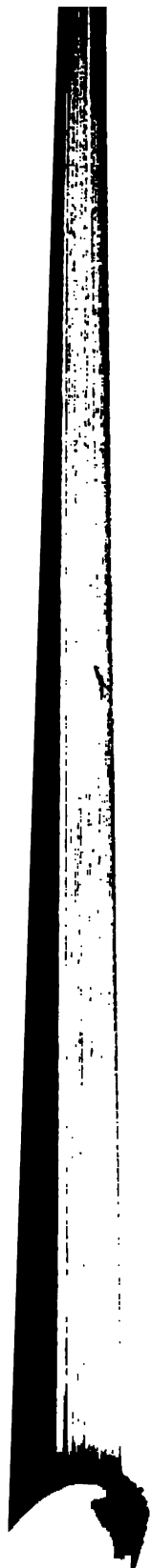
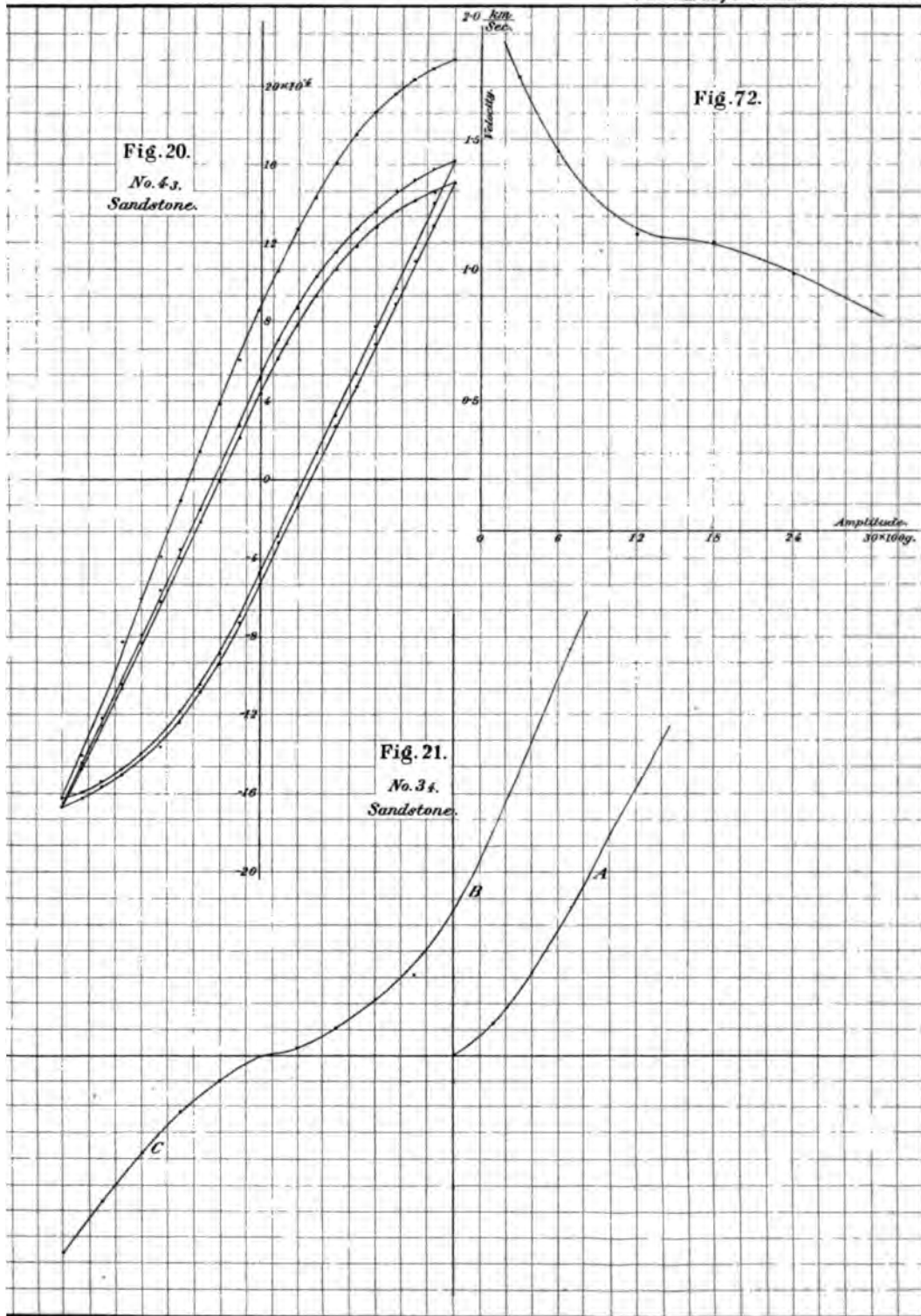


Fig.19.
No. 34.
Sandstone.

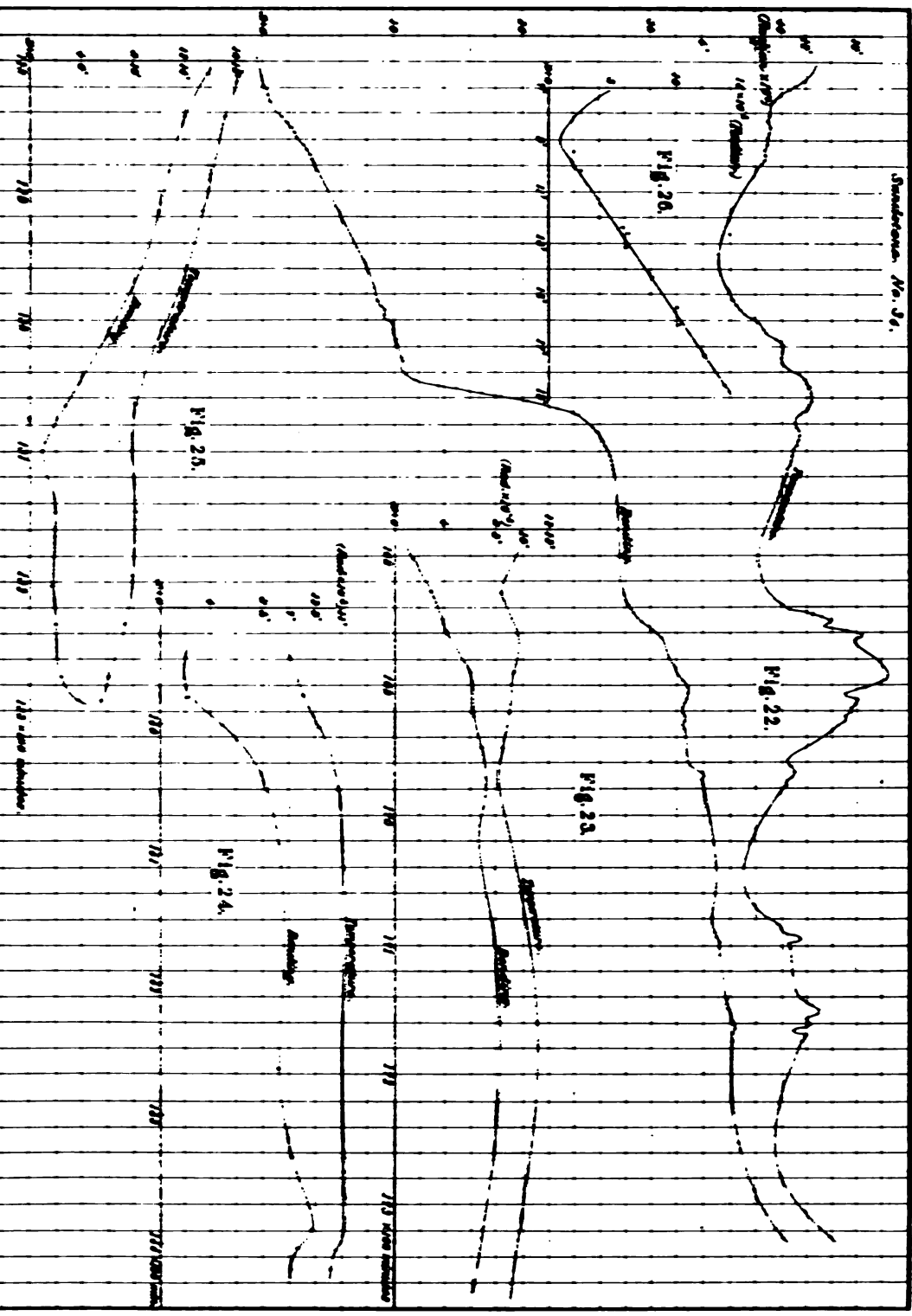




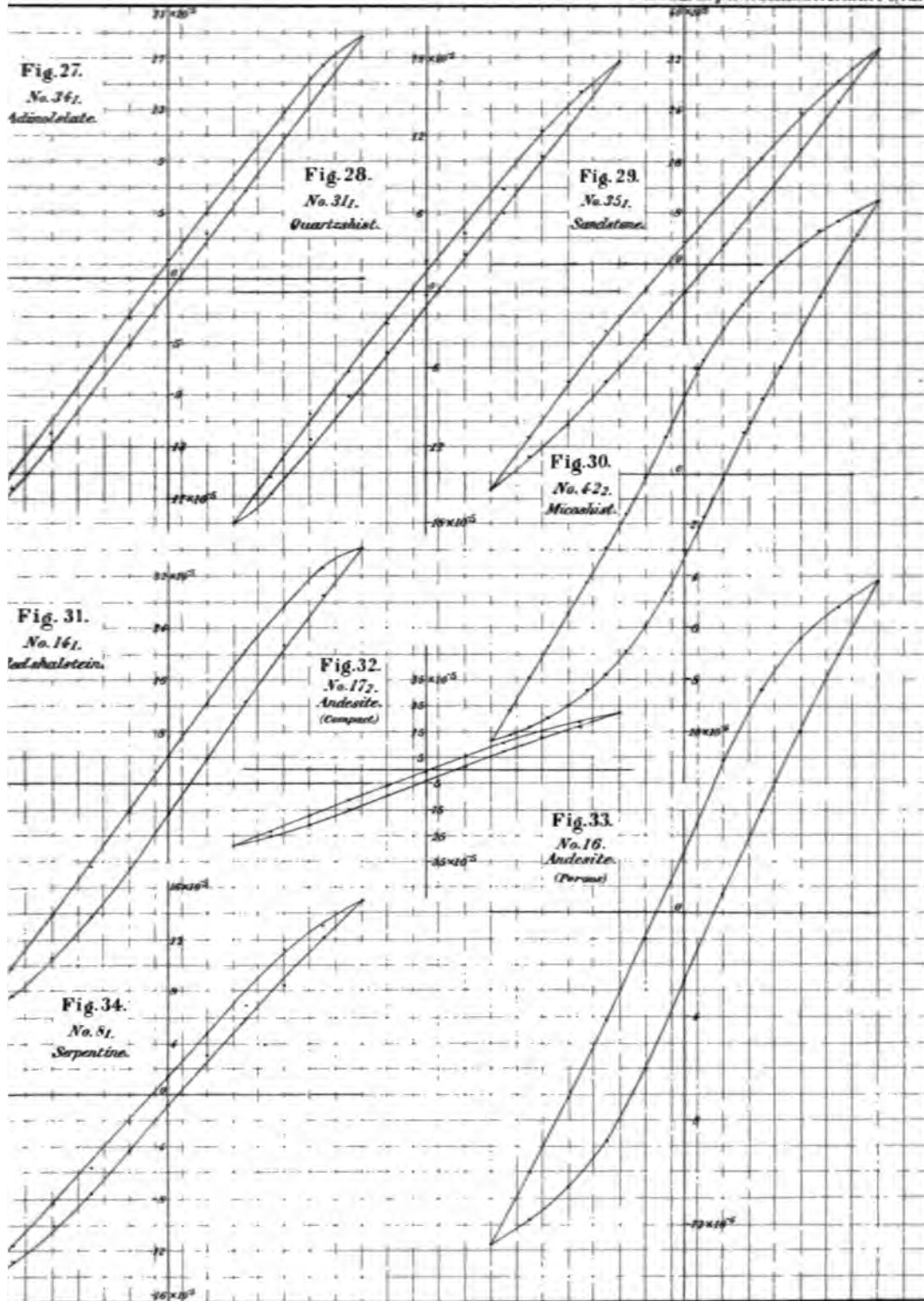


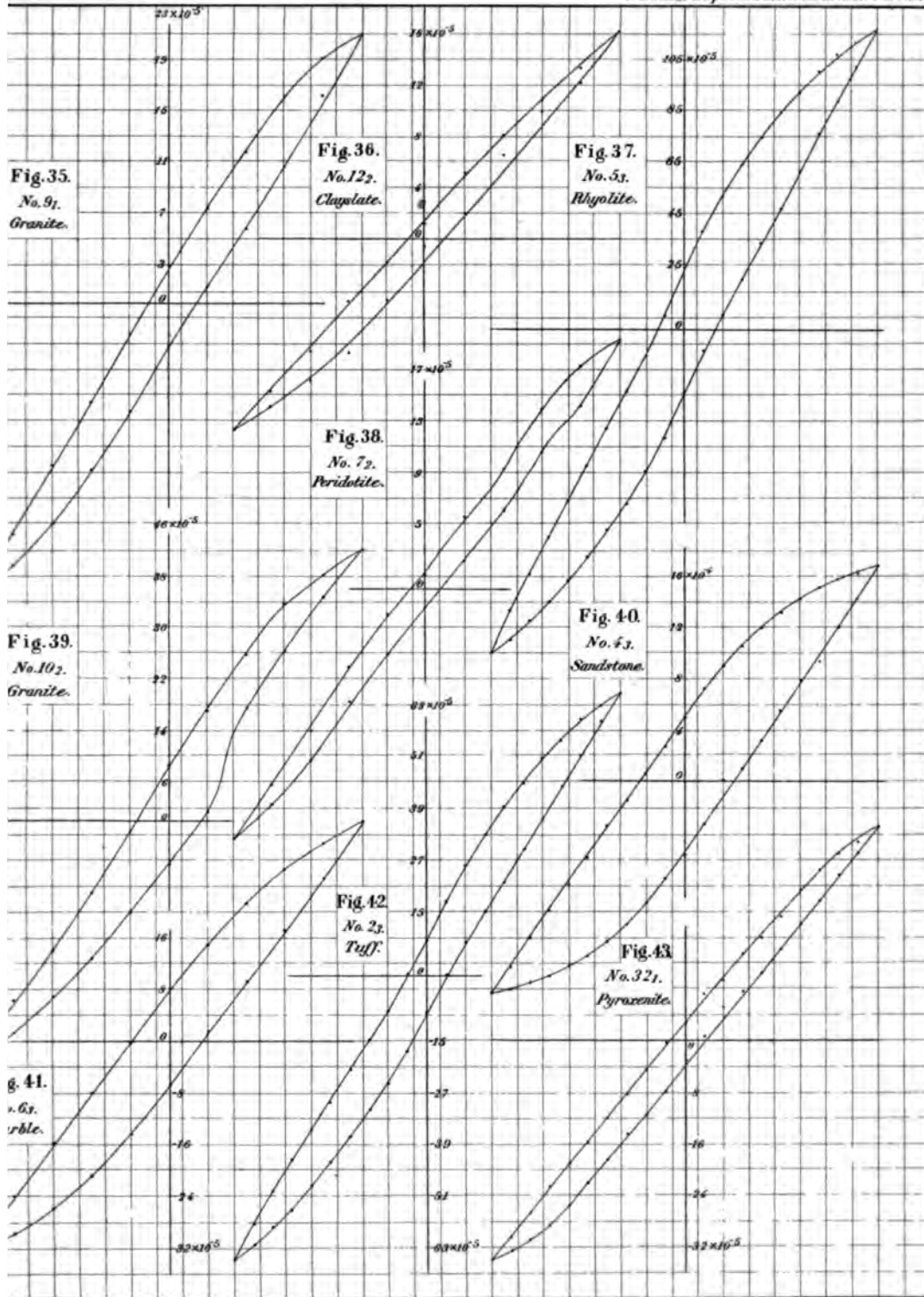
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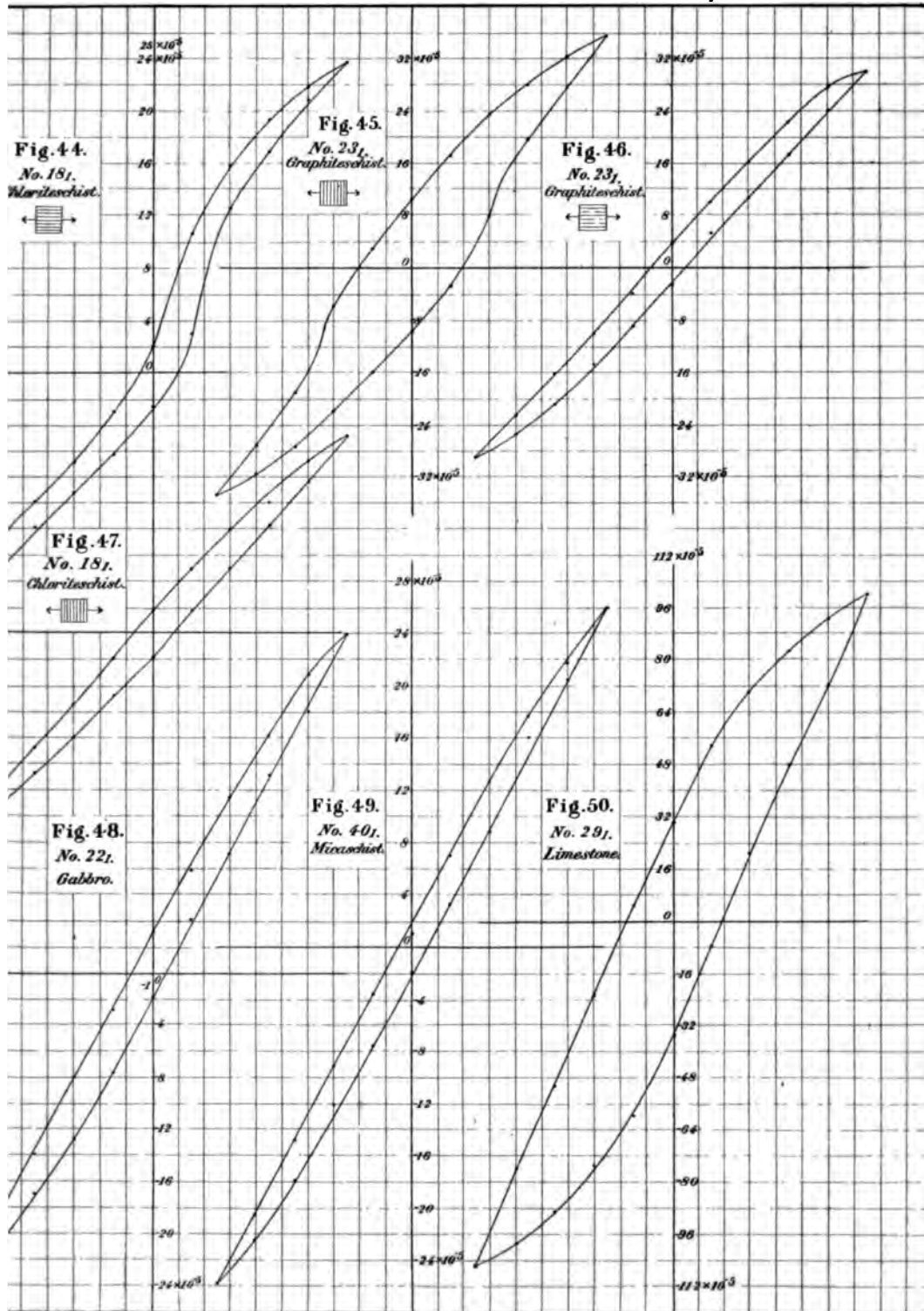
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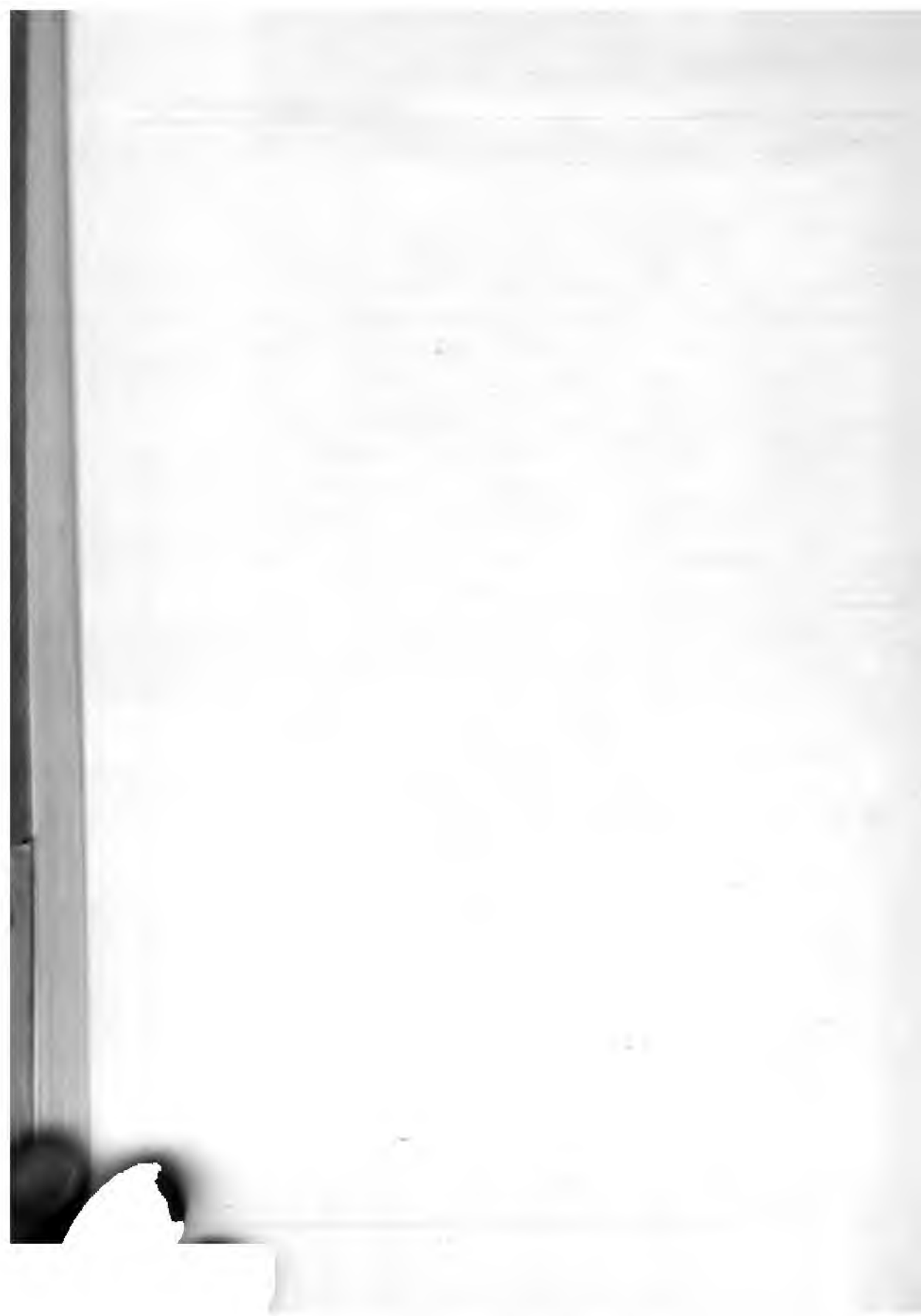


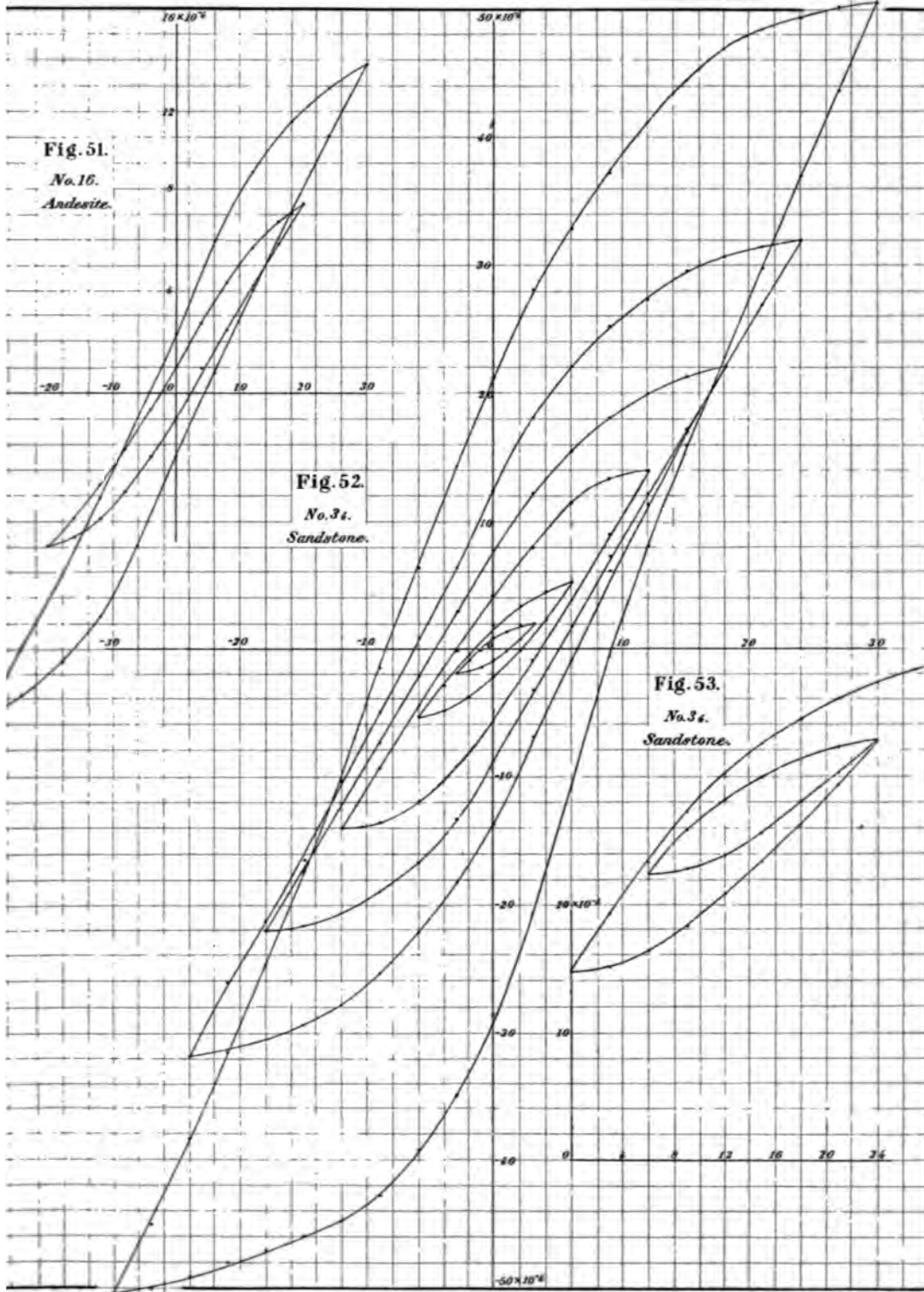




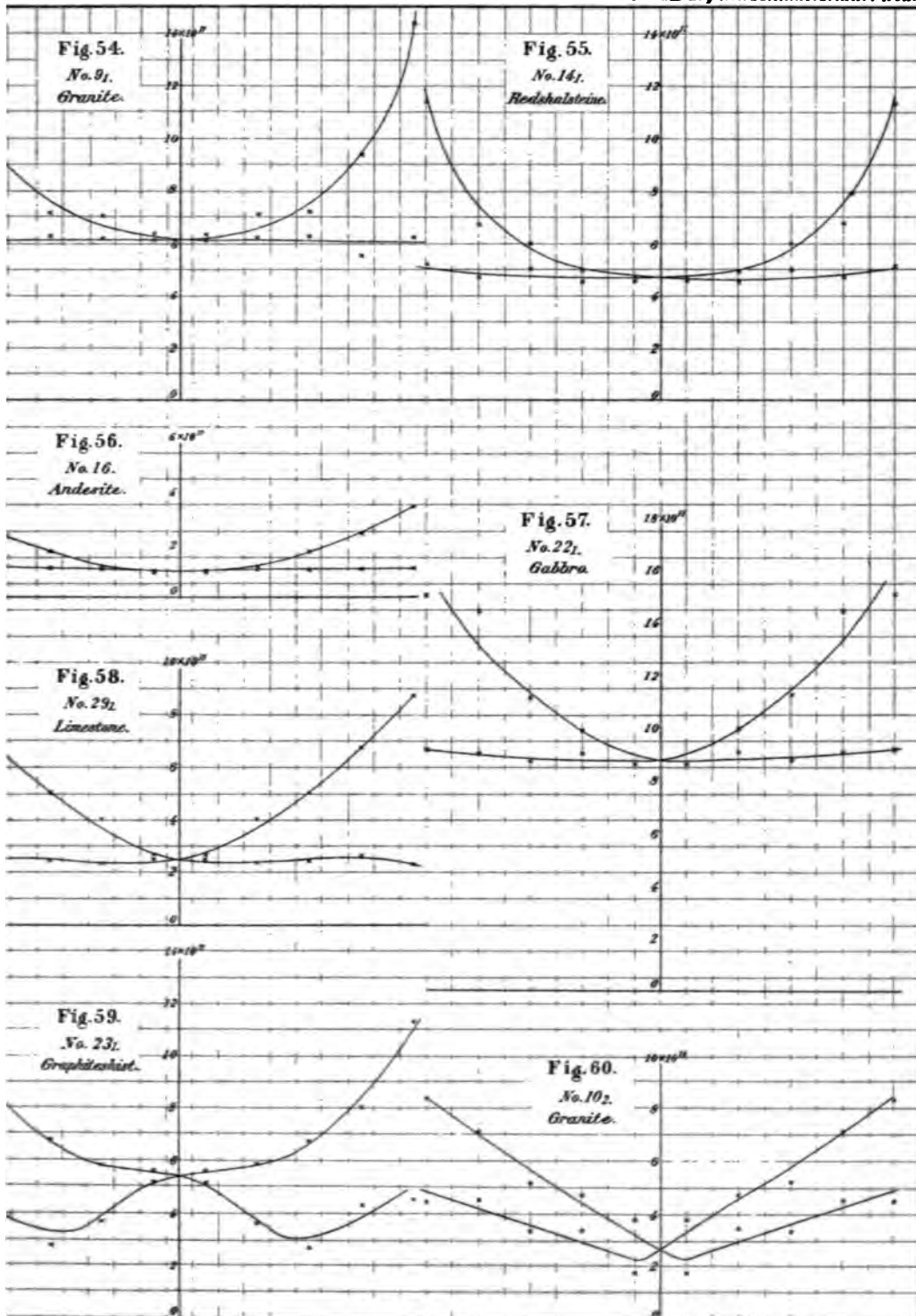








2





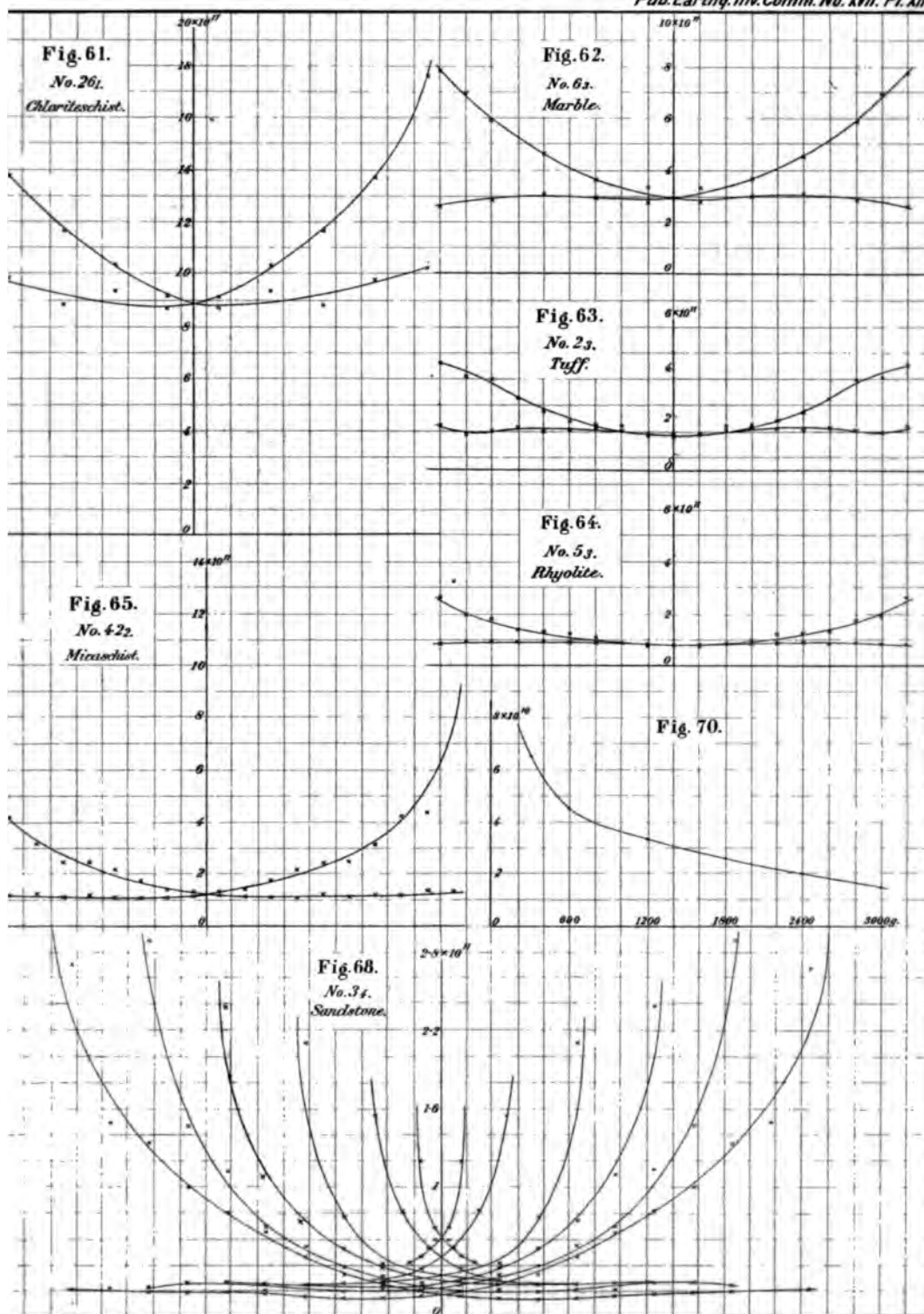




Fig. 66.

Upper branch: $E=0.243+0.92.X^2$
Lower branch: $E=0.243+0.043.X^2$

E

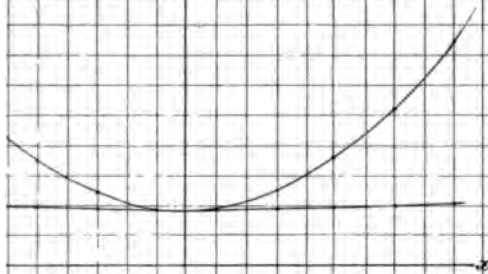


Fig. 67.

$$y = C \Sigma \frac{y^2}{x^2} + \text{Const.}$$

y

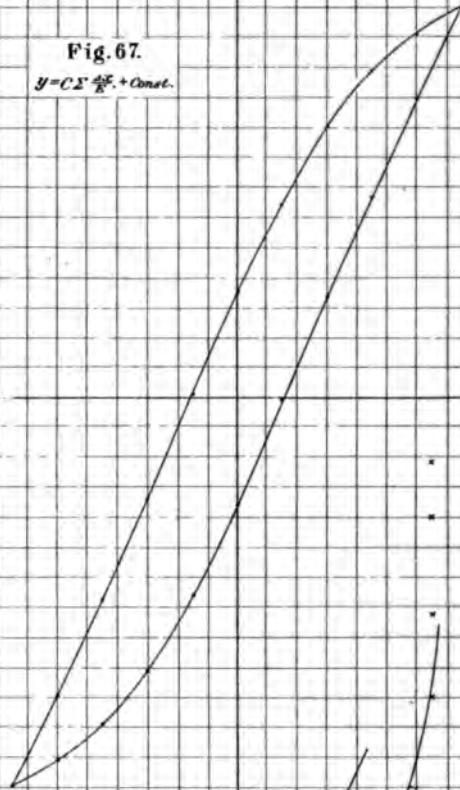


Fig. 71.

No. 43.
Sandstone.

B

32
24
16
8
0

A

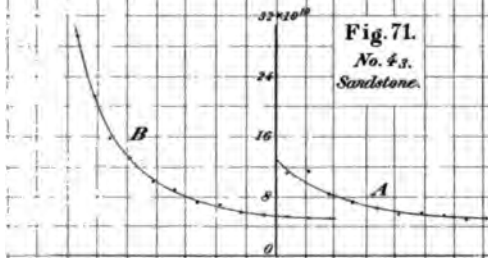
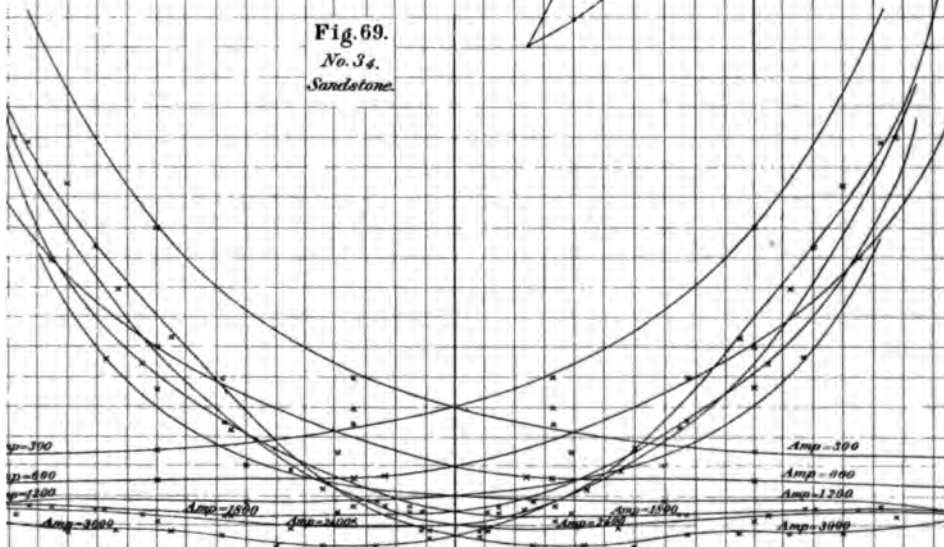


Fig. 69.

No. 34.
Sandstone.



1

Fig. 75.

Pub. Earthq. Inv. Comm. No. XVII. Pl. XIV.



Fig. 73.

$$F = ch \log \left(1 + \frac{p^2}{2p+1} + 2p+1 \cdot t + t^2 \right).$$

Fig. 74.

$$\begin{aligned} \text{Curve a } F &= \frac{h}{t+1} \\ \text{Curve b } F &= \frac{h}{t+1} - \frac{h}{p} \log \left(1 + \frac{T}{t+1} \right) \\ \text{Curve c } F &= \frac{h}{t+1} - \frac{h}{p} \log \left(1 + \frac{T}{t+1} \right) \end{aligned} \quad \left\{ \begin{array}{l} T=1000 \\ T=100 \end{array} \right.$$

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A Duplex Horizontal Pendulum Apparatus.¹⁾

By

F. Omori, *Rigakushi, Rigakuhakushi,*

Member of the Imperial Earthquake Investigation Committee.

With Plates I and II.

The duplex horizontal pendulum apparatus, which is shown in fig. 2, Pl. I, is an improved form of the mechanically registering seismograph, which I have used for some years²⁾; the modification consisting in the introduction of the principle of the duplex pendulum of Professors Gray, Ewing and Milne. The essential part of the instru-

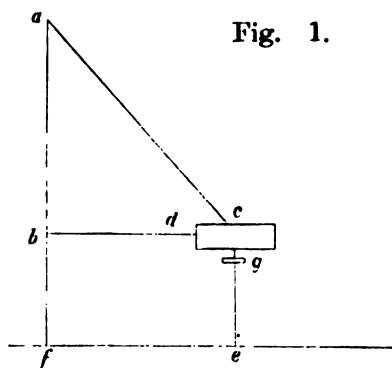


Fig. 1.

ment, which is shown in the accompanying figure, is made up of a heavy flat cylinder *c* (fig. 1) of brass filled with lead, about 16 kg in weight, suspended from the top, *a*, of a strong cast iron stand *af*, which is bolted at *f* to the foundation stone, *fe*; the strut *db* being pivoted at *b*. The pendulum *c*, which

is first brought very nearly to a state of neutral equilibrium, is to be further adjusted by means of an inverted pendulum *ge*. The mechanical details of the latter as well as the recording arrangement are shown in Pl. II.

Pl. II. The auxiliary inverted pendulum consists of a light alu-

1) A short preliminary description of this instrument has been given in Tokyo Sngaku-Butsuri Gakkwai Kiji Gaiyō, Vol. II, No. 8, Jan., 1904.

2) See the *Publications*, No. 5.

minium tube eg , about 30 cm in length, carrying a small metallic disc g , about 0.017 kg in weight, put very closely to the heavy bob c . The upper end of the tube eg is furnished with a brass fork, between whose two limbs fits exactly a highly polished steel axis h , about 2 mm in diameter and 3 cm in length, pivoted between two small supports, ii , attached to the lower face of the heavy cylinder c ; the axis h being parallel to the strut. The lower end of the tube eg is furnished with two foot-screws, jj , which fit respectively in a conical socket and in a V-groove, mounted on a base plate k . The line formed by joining the apex of the socket and the vertex of the V-groove is to be brought exactly below and parallel to the axis h , by means of the screws l, l, m , which move the plate k in two rectangular horizontal directions.

It will thus be seen that the inverted pendulum eg can rotate only about a line parallel to the equilibrium position of the strut, its upper part being joined to the heavy weight in such a way that the friction at the point of contact is reduced to a minimum. Now, the equilibrium of a horizontal pendulum has always a certain degree of stability, which depends on the angle φ , formed by the vertical and the line joining the point of suspension, a , with the point of support, b ; this angle being determined by the well known relation

$$\varphi = \frac{T_0^2}{T^2},$$

in which T is the period of oscillation of the horizontal pendulum (when not joined to the inverted pendulum), and T_0 the period when the system formed by the strut bd and the heavy bob c is made to swing as an ordinary vertical pendulum. If W and w denote respectively the weights of the heavy bob c and the small disc g , we have, for making neutral the equilibrium of the horizontal pendulum, the following relation:—

$$w = W \times \frac{H \cdot \varphi}{L},$$

in which L is the length between the centre of the heavy bob c and the point of support b , and H is the height of the inverted pendulum

eg. To take an example, let $W=15$ kg, $L=100$ cm, $H=30$ cm, and $\varphi = \frac{2 \times 2}{30 \times 30}$; we then find $w=0.02$ kg.

The mechanism at the top, a , of the cast iron stand, the multiplying pointer, and the record-receiver whose details will be seen from figs. 3 and 4, Pl. I, and from Pl. II, are exactly similar to those in the older instruments. With a portable instrument of this description, in which the length bc and the height ab is each equal to 1 metre, the complete period of free oscillation of the steady mass can be raised without much difficulty to 1 minute, the multiplication of the recording pointer being 20 to 30.

Tokyo. June, 1904.

Fig. 3.

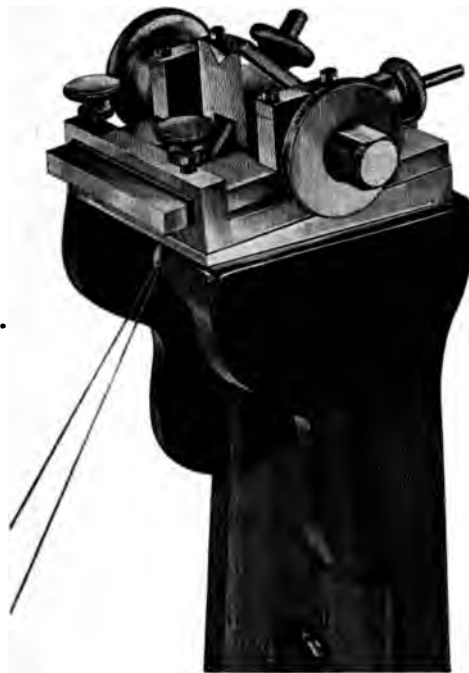
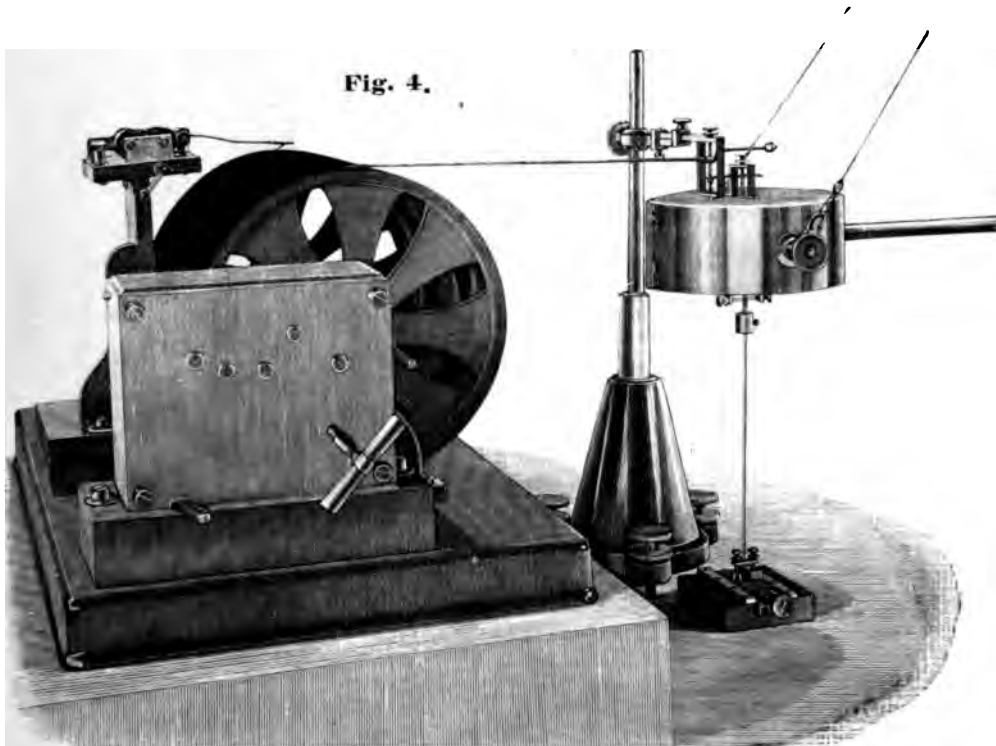
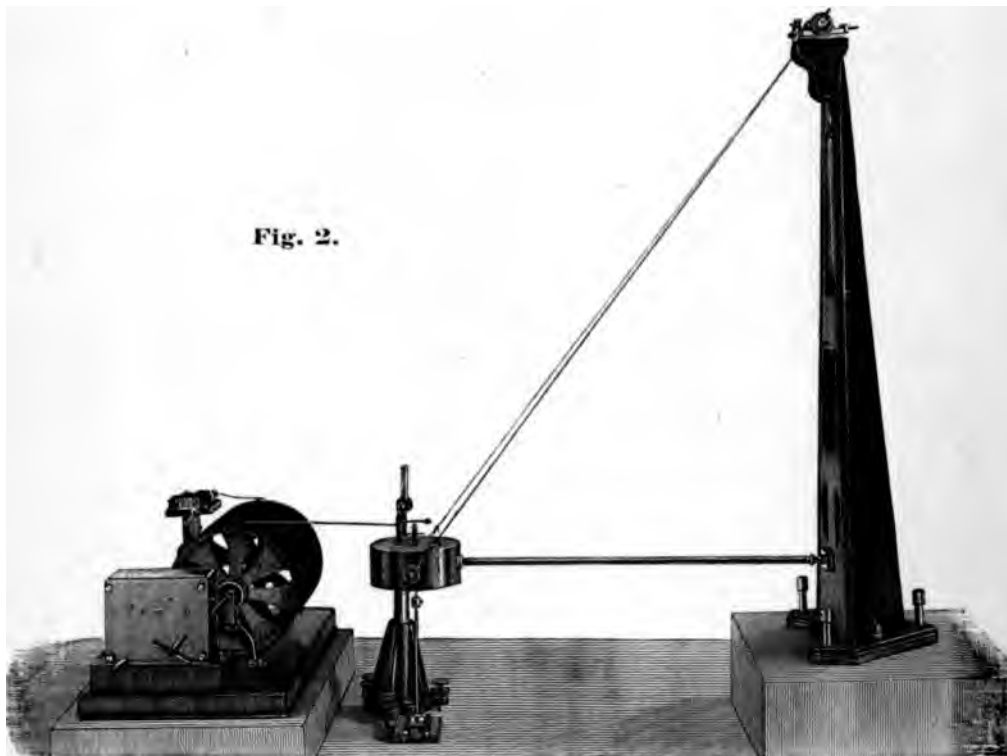


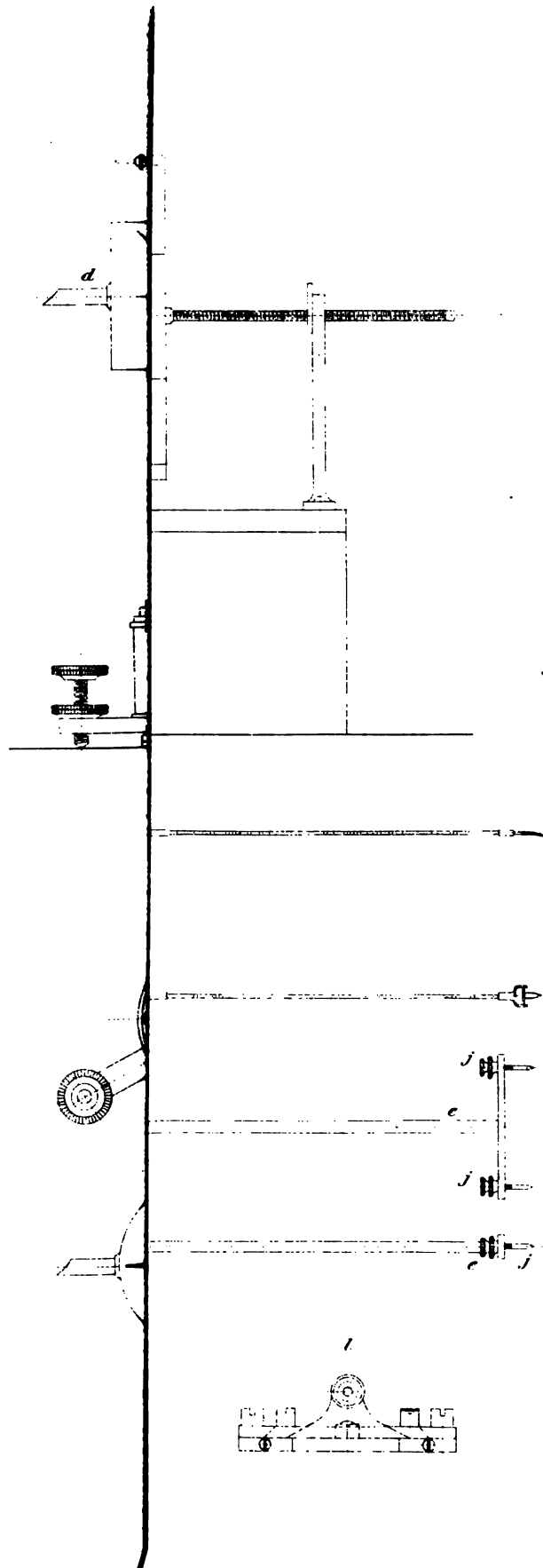
Fig. 4.



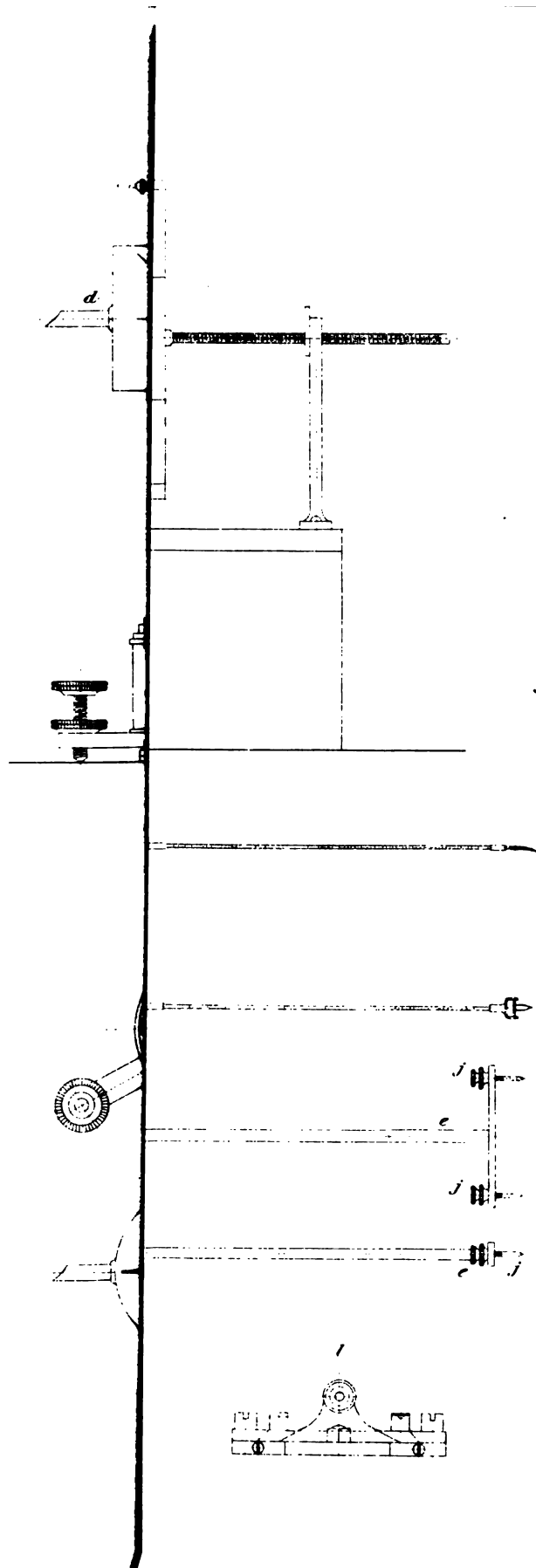
Duplex Horizontal Pendulum
Apparatus.



Pl. II.



PL II.





A Horizontal Tremor Recorder.

By

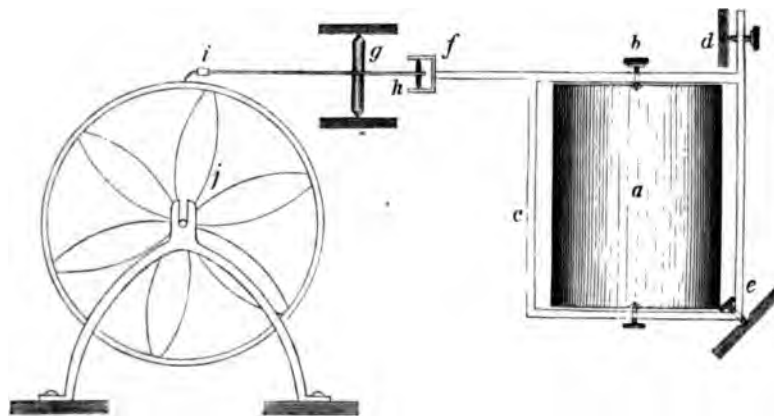
F. Omori, *Rigakushi, Rigakuhakushi,*

Member of the Imperial Earthquake Investigation Committee.

With Plates III and IV.

1. The Metropolitan Police had recently to consider several cases of complaints respecting the disturbances caused by steam engines, dynamos, etc. to neighbouring buildings; and the instrument which I am going to describe in the following pages has been constructed to measure the horizontal movement due to the above mentioned causes.

Fig. 1.



2. The essential part of the instrument, which is diagrammatically shown in fig. 1, consists of a vertical brass cylinder, *a*, 16 cm in height and 10 cm in diameter, filled with lead, and about 15 kg in weight, pivoted in a strong iron frame *bc*, the latter being supported by means

of two screw points d and e from a strong brass stand, about 20 cm in height and furnished with three levelling screws exactly in the same way as in Prof. Ewing's horizontal pendulum. The distance between the pendulum axis and the centre of the heavy cylinder, or the steady point, is 6 cm ; while there is attached to the iron frame in way of prolongation a stout aluminium rod bf , whose length is 15 cm. The horizontal motion, whose direction is normal to the pendulum plane, will thus be magnified $3\frac{1}{2}$ times at the end of the aluminium prolongation. There is, however, an independent multiplying pointer, consisting of a vertical axis, g , which is pivoted in an inverted bracket properly attached to an upright support, and which carries a horizontal light lever hgi . The shorter arm of the latter consist of a thin brass piece formed into a fork between whose two limbs fits exactly a highly polished axis of steel, h , pivoted in a small bracket attached to the end of the strong aluminium prologation before mentioned. The longer arm of the lever consists of a tapering tube of aluminium, 120 mm in length, at whose end, i , is hinged an index which writes on a smoked paper wrapped round a drum, j , driven by a clock work. In other instruments, the record is taken in ink on a white band of paper driven by means of rollers, as in the *vibration measurers* for bridges, railway carriages, etc. It will be observed that the multiplying arrangement here employed is perfectly similar to that in the horizontal pendulums for the observation of distant earthquakes. As the minimum effective length of the shorter arm of the multiplying lever is 6 mm, the writing index records the motion $20 \times 3\frac{1}{2} = 70$ times magnified ; it being, however, also possible to reduce the magnification ratio down to 10, by suitably changing the effective distance of the shorter arm of the pointer. The mechanical details and the photograph* of the instrument are given in figs. 2, 3, 4 and 5, Pl. III.

For the complete observation of the horizontal motion, we require,

* The photograph represents an instrument which is slightly different from that whose mechanical details are given in the Plate, the record being taken on a smoked paper.

of course, a pair of these instruments, with their pendulum planes at right angles to one another.

The horizontal tremor recorder has already been used in a few cases, of which the following are examples.

3. *Shakings in the Hospital of the Tōkyō Imperial University, Hongō.* Towards the end of 1903 and in the beginning of 1904, the Medical Laboratory in the Hospital of the Imperial University, Hongō, was subject from time to time to *unfelt shakings*, which caused windows to rattle and bottles placed on tables to rock. On inquiry, these effects were traced to be due to the working of a small oil engine of 10 horse power, temporarily set up in the University compound; the engine being about 87 metres to the NW of the Medical Laboratory, which is a low wooden structure. When observed on Jan. 8th, 1904, at 10 am., the movements of the windows and bottles were executed in a quite regular way at the rate of about 4 in a second and were sufficiently well pronounced as to constitute a source of disturbance to the people sitting in the room. The floor itself, however, indicated no *sensible* motion.

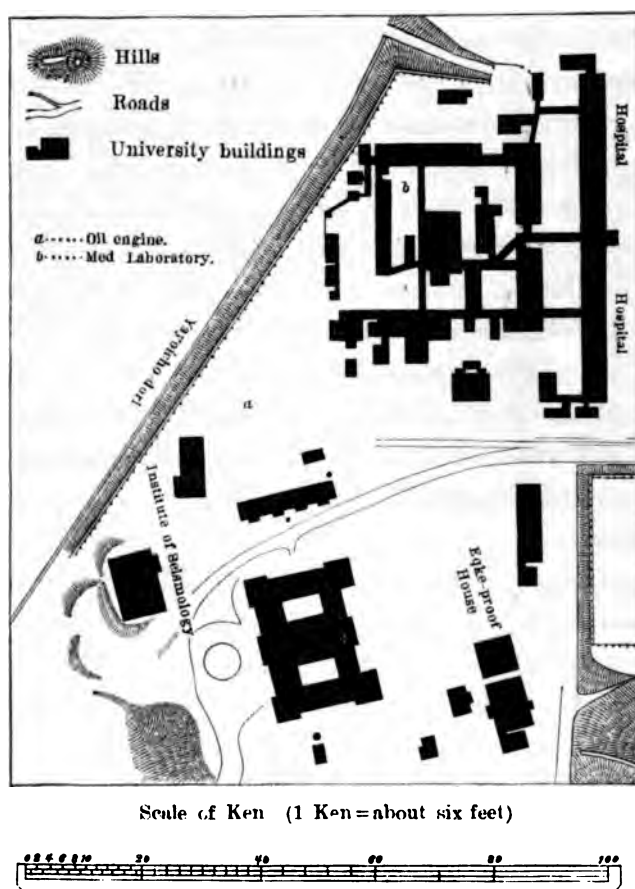
The movements on the date above mentioned, which were measured by a tremor recorder set up on the floor of the laboratory, consisted of a series of regular and nearly uniform vibrations, whose double amplitude was, in each of the EW and NS components, about 0.02 mm, and whose period was 0.24 sec., corresponding to 250 revolutions per minute of the engine. The absolutely greatest movements in the EW and NS components were respectively 0.028 and 0.034 mm.

The disturbances due to the same source were simultaneously measured in the brick Earthquake-proof House, which is situated at a distance of about 110 metres to the south-west of the oil-engine. The movements there measured, on the solid concrete basement, were much smaller than in the Medical Laboratory, and consisted of a series of maximum groups, the absolutely greatest double-amplitude in the NS direction being 0.026 mm. The period was 0.24 sec.

The positions of the oil engine, the Medical Laboratory, and

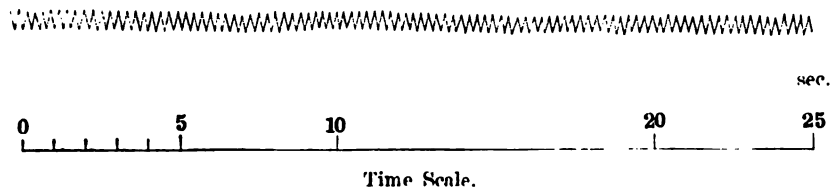
the Earthquake-proof House, are indicated in the accompanying plan of a part of the University compound.

Fig. 6. Plan of a part of the Tōkyō Imperial University compound.



4. *Movement in the Seismological Institute.* On May 19th, 1904, the effects of the oil engine mentioned in the preceding § were very markedly indicated in the Seismological Institute, which is a one-storied wooden building. Fig. 7 is a part of the NS component diagram obtained on the above date by means of a horizontal tremor recorder set up on a solid brick column in one of the instruments rooms, whose

Fig. 7. Vibration caused by an Oil Engine.
NS component. Multiplication = 29.



distance from the engine was about 70 metres: the positions of the Institute being shown in the map (fig. 6). The max. double amplitude was 0.09 mm and the period was 0.227 sec., corresponding to 265 revolutions per minute of the engine. The movements were perceptible and sufficiently intense to produce considerable amount of the rattling of the windows.

5. *Miscellaneous experiments.* (Pl. IV.) Fig. 8 and 9 are parts of the diagrams of the longitudinal motion of the ground at the distances respectively of about 17 and 60 feet from a small oil engine of the workshop of the Physical Institute. Again, figs. 10 and 11 represent the normal vibrations respectively of the eastern and southern up-stair walls of the workshop of the Mechanical Institute of the Engineering College due to the working of a small steam engine which is situated close to the southern wall.

The following table gives the results of the measurements made in 1903.

Place of observation.	Cause of disturbance.	Direction of the motion measured.	Distance between the origin of disturbance and the place of observation.	Max. double-amplitude.	Period of vibration.
			Feet.	mm	sec.
Upper-story floor of the Workshop of the Mech. Inst., Tokyo Imp. Univ.	A steam engine in the Workshop of the Mech. Inst., Tokyo Imp. Univ.	Normal to the E. end wall.	(Near to the E. end wall.)	0.018	0.09
		Parallel " to the S. end wall.	(Near to the S. end wall.)	0.016	0.17
		"	"	0.050	0.043
		"	"	0.016	0.097
Ground floor of the same Workshop.		Parallel to the piston of the engine.	18	0.015	0.071
Ground surface.	An oil-engine in the Workshop of the Physical Inst., Tokyo Imp. Univ.	45° to the direction of the piston.	90	0.02	0.10
		At right angles to the direction of the piston.	60	0.03	0.12
		45° to the direction of the piston.	9	0.17	0.25
Ground surface.	An engine in a crucible factory, at Shiba, Tokyo.	Parallel to the direction of the piston.	18	{ 0.02 0.007	{ 0.23 0.058
At right angles to the direction of the piston.		"	0.012	0.20	
—		48	0.067	0.087	
Parallel to the direction of the piston.		170	Very slight.	—	
Parallel to the direction.		78	0.018	0.12	
Normal to the direction of the piston.		"	0.01	0.18	
On the floor of a one-storied wooden house.		Normal to the direction of the piston.	60	{ 0.018 0.022	{ 0.24 0.086
Parallel to the direction of the piston.		"	0.02	0.23	

From the above table, it will be seen that the movements measured were usually very small and amounted, at a distance of a few dozen metres from the origin of disturbance, to only a few hundredths of a mm; it being extremely rare that the double amplitude reaches some tenths of a mm. The period varied between 0.058 and 0.25 sec.

It is to be remarked that the motion of a wall (or house) is, for evident reasons, generally much greater than that of the ground on which it stands. Thus in the case of the Workshop of the Mechanical Institute of Tokyo Imperial University, the normal motion of one of the upper story walls amounted to 0.05 mm (period=0.043 sec.), while that on the ground at a distance of 18 feet from the engine was 0.015 mm (period=0.071 sec.). Similarly in cases of actual earthquakes, buildings generally act more or less as a kind of seismoscope, being sometimes thrown into vibrations many times larger than the motion of the ground.¹⁾

6. *Sensible limit of small motion.* For practical purposes, it is desirable to fix the sensible limit of small motion in the disturbances of artificial origins. This is, however, a difficult problem, since the limit in question would be widely different for different persons. The following result is to be regarded only as a provisional one.

From the study of the macro-seismographic diagrams obtained in Tokyo, the least value of the intensity, or maximum acceleration ($=a$), of the sensible earthquake motion seems to be about 17 mm per sec. per sec. Denoting by T and $2a$ respectively the period and the double amplitude of a motion of sensible limit, we have

$$a = \frac{2\pi^2 \times 2a}{T^2}, \quad \text{or} \quad 2a = \left(\frac{a}{2\pi^2} \right) \times T^2 = 0.86 \times T^2,$$

which latter equation gives the range of motion corresponding to a specified value of the period T . The figures contained in the following table have been calculated according to the above formula.

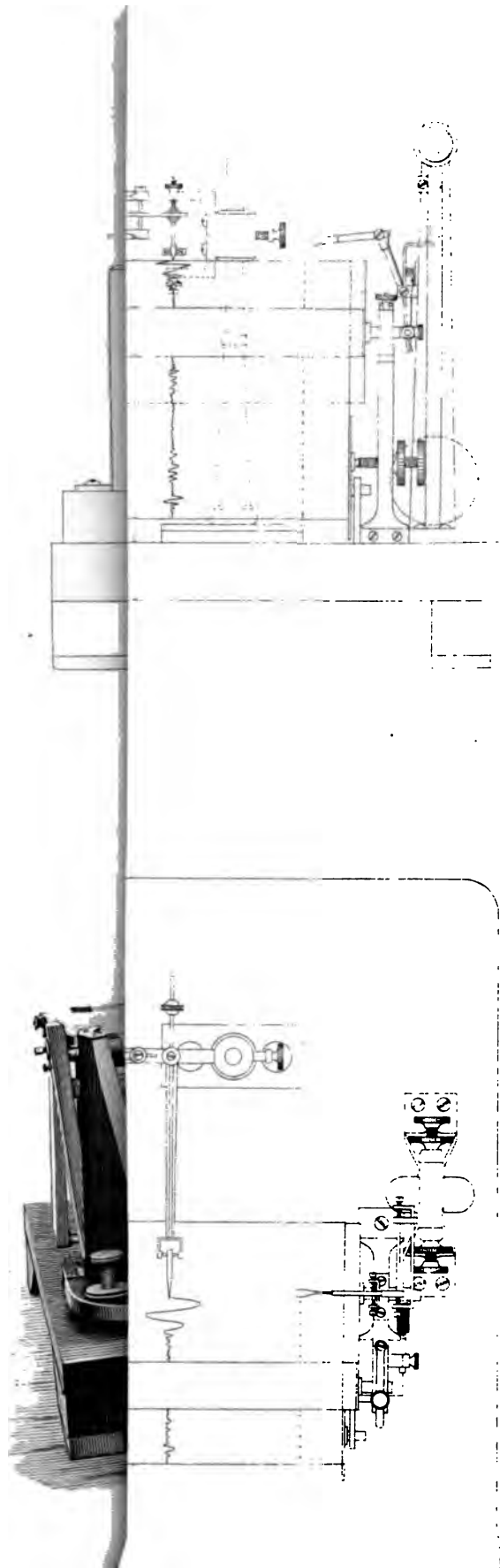
1) See Prof. Milne: "Seismic Survey," Trans. Seism. Soc., Vol. X; and F. Omori: "Earthquake Measurement in a brick building," and "Motion of a Brick Wall produced by earthquakes," the Publ. of the Earthq. Inv. Com., Nos. 4 and 12.

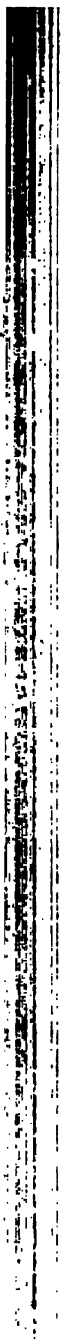
T	$2a$	T	$2a$
sec.	mm.	sec.	mm.
0.10	0.009	0.043	0.0016
0.11		...	...
0.12	0.012		
...	...	0.07	0.004
...	...	0.08	0.006
0.20	0.034	0.09	0.007
0.21	0.038		
0.22	0.042		
0.23	0.046		
0.24	0.050		
0.25	0.054		

Thus it will be observed that, with periods of 0.10 and 0.20 sec., the motion will become sensible respectively at ranges of about 0.01 and 0.03 mm. It is hereby to be noted that the quantities a , $2a$ and T relate all to the motion of the *ground*, which will be just strong enough to be felt by people sitting in wooden houses.

Tokyo. June, 1904.

PL. III.





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Note on the Relation between Earthquakes and Changes in Latitude.

By

F. Omori, *Riyakushi, Rigakuhakushi,*

Member of the Imperial Earthquake Investigation Committee.

With Plates V and VI.

1. *Introduction.* The relation between earthquakes and changes in latitude is one of the subjects whose investigation was undertaken by the Imperial Earthquake Investigation Committee,¹⁾ which instituted in 1895 the observation of latitude variation in Tokyo by means of a Wanschaff's zenith telescope of 81 mm aperture.²⁾

I give next a short account of what has already been done by seismologists in this connection, and then proceed to compare the seismic frequency in Japan with changes of latitude in Tokyo.

2. In the British Association Report for the year 1900, Prof. Milne gives, for the years 1895 to 1898 inclusive, a comparison of the wanderings of the pole from its mean position with the registers of earthquakes which have disturbed the whole world, or, at least, continental areas; the conclusion arrived at being that when the pole displacements were comparatively great large earthquakes were frequent and *vice versa*. Prof. Milne's results are as follows.

1) See Baron Kikuchi's Preface to No. 1 of the *Publications*; also No. 1 of the *Reports* (Japanese), published in 1893.

2) In 1898, the work of the latitude observation in Tōkyō has been transferred to the Imperial Geodetic Commission. The observations were made first by Dr. H. Kimura, and subsequently by Mr. K. Hirayama.

Year	Total latitude variation.	Number of large earthquakes.
1895	0.53	9
1896	0.91	18
1897	1.07	44 or 47
1898	1.03 ¹⁾	30

Prof. Milne's investigation was continued by Dr. A. Cancani, who obtained, for the years 1899 to 1902 inclusive, the following results.²⁾

Year.	Total latitude variation.	Number of large earthquakes.
1899	0.72	27
1900	0.32	17
1901	0.53	22
1902	0.97	29

The inference to be drawn from the above table is similar to that already obtained by Prof. Milne, namely, that the total annual amount of the latitude variation was greater or smaller according as the number of large earthquakes was large or small.

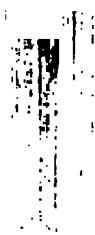
In the British Association Report for the year 1903, Prof. Milne examines the numbers of large earthquakes in the ten parts, into which each of the years, 1892 to 1899, is divided; the results of the investigation being that this same type of earthquakes has been frequent when the change in direction of the movement of the pole has been marked.

§ 3. *Latitude variation at Tokyo.* The following table gives the mean monthly values of the latitude of Tokyo (the Astronomical Observatory) for nearly 8½ years between Aug. 1895 and Dec. 1903; the results being graphically illustrated in fig. 1.

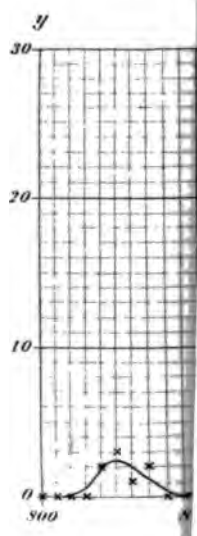
1) Adopting the value corrected by Dr. A. Cancani.

2) Dr. A. Cancani: *Sopra un' ipotetica relazione fra le variazioni di latitudine e la frequenza dei terremoti mondiali.* Boll. della Soc. Sism. Italiana, Vol. VIII.

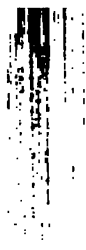




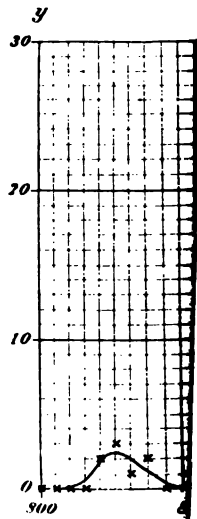
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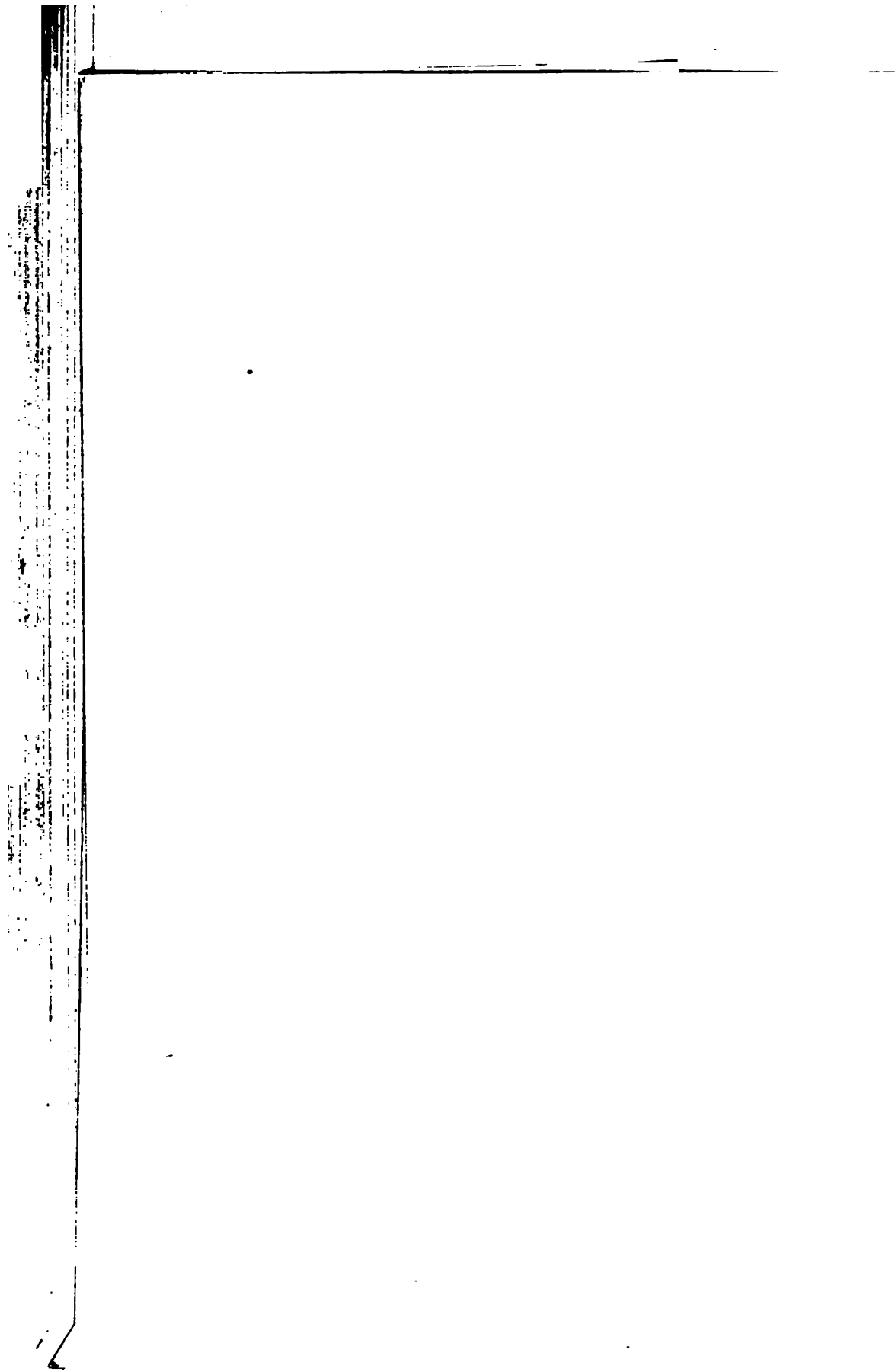


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RESULTS OF LATITUDE OBSERVATIONS AT TOKYO.

AUG. 1895—DEC. 1903.

Mean date.	Decimal of the year.	Latitude.	Mean date.	Decimal of the year.	Latitude.
1895 Aug. 12	1895.61	35°39'16".59	1900 Apr. 18	1900.30	35°39'16".84
Sept. 14	70	16.71	May 13	37	16.81
Oct. 18	80	16.72	June 13	45	16.82
Nov. 16	88	16.81	July 26	57	16.81
Dec. 15	96	16.80	Aug. 15	62	16.76
1896 Jan. 32	1896.06	16.75	Sept. 18	72	16.79
Feb. 12	12	16.73	Oct. 15	79	16.88
Mar. 16	21	16.68	Nov. 15	87	16.82
Apr. 13	28	16.60	Dec. 12	95	16.79
May 16	37	16.57	1901 Jan. 16	1901.05	16.76
June 15	46	16.47	Mar. 23	23	16.70
Sept. 20	72	16.69	Apr. 13	28	16.70
Oct. 19	80	16.83	May 18	38	16.69
Nov. 12	87	16.84	June 16	46	16.67
Dec. 12	95	16.87	July 26	57	16.69
1897 Jan. 13	1897.07	16.85	Oct. 22	1901.81	16.98
Feb. 13	12	16.85	Nov. 22	89	17.04
Mar. 16	21	16.78	Dec. 14	95	17.01
Apr. 23	31	16.77	1902 Jan. 13	1902.04	16.98
May 19	38	16.59	Feb. 15	13	16.85
June 13	45	16.52	Mar. 13	20	16.83
July 18	55	16.41	Apr. 16	29	16.67
Aug. 17	63	16.39	May 16	37	16.64
Sept. 15	71	16.54	June 10	44	16.62
1898 Oct. 15	1898.79	16.58	July 13	53	16.67
Nov. 12	87	16.78	Aug. 28	66	16.86
Dec. 14	95	16.88	Sept. 18	72	16.92
1899 Jan. 19	1899.05	16.95	Oct. 16	79	16.95
Feb. 11	12	16.94	Nov. 15	88	17.02
Mar. 20	23	17.02	Dec. 19	97	17.03
Apr. 18	30	17.02	1903 Jan. 15	1903.04	17.04
May 15	37	16.95	Feb. 15	13	16.92
1899 June 12	1899.45	16.85	Mar. 13	20	16.85
July 21	55	16.66	Apr. 16	29	16.75
Aug. 17	63	16.60	May 16	37	16.61
Sept. 13	70	16.61	June 13	45	16.54
Oct. 18	80	16.68	July 22	56	16.53
Nov. 15	87	16.67	Aug. 20	64	16.56
Dec. 24	98	16.69	Sept. 15	71	16.61
1900 Jan. 21	1900.06	16.73	Oct. 16	79	16.69
Feb. 16	13	16.77	Nov. 13	87	16.77
Mar. 17	21	16.81	Dec. 17	96	16.89

To see the relation, if any, between the latitude variation in Tokyo and the frequency of large Japan earthquakes, the latter are marked along the abscissa or time axis of the diagram (fig. 1); each black dot (•) denoting a great and more or less destructive shock, while a small circle (○) denotes a large earthquake which was not destructive, but whose area was extensive and about 10,000 square *ri*¹⁾ or more.

An examination of fig. 1 shows that all the destructive earthquakes occurred exactly or very nearly at those epochs when the latitude was at a maximum or a minimum. The non-destructive extensive earthquakes indicate also a similar tendency, though in a less marked degree.

Note. From fig. 1 it will be at once observed that the curves *b* and *c* and the curves *b'* and *c'* are nearly symmetrical with respect to the curve *a*; *b* and *c* correspond to the epoch June 1901 to June 1903, *c'* and *b'* to the epoch Aug. 1897 to Aug. 1899, while *a* corresponds to the epoch Aug. 1899 to June 1901. The latitude variation was smallest in the epoch denoted by the curve *a*.

The following table contains a list of the successive epochs of the different phases of the latitude variation, deduced directly from the diagram (fig. 1), each sign (×) denoting a destructive earthquake. It will be seen that all the destructive earthquakes occurred during the epochs of the maximum and minimum latitude, as above stated.

Minimum Latitude.	Maximum Latitude.	Decreasing Latitude.	Increasing Latitude.
Year. Month.	Year. Month.	Year. Month.	Year. Month.
1896, VI-VIII. ××	1895, XI-XII.	1896, I-V.	1895, VIII-X.
1897, VII-VIII. ×	1896, X-1897, II. ×	1897, III-VI.	1896, IX.
1898, IX. ×	1899, I-V. ××	1899, VI.	1898, X-XII.
1899, VII-XII.	1900, IV-XI. ×	1901, I.	1900, I-III.
1901, II-VIII. ××××	1901, X-1902, I. ×	1902, II-III.	1901, I-X.
1902, IV-VII.		1903, II-V.	1902, VIII-X.
1902, XI-1903, I.			1903, IX-XII.
1903, VI-VIII.			
Aggregate duration = 26 months.	Aggregate duration = 16 months.	Aggregate duration = 14 months.	Aggregate duration = 14 months.

1) 1 *ri* = 4 km nearly.

4. *Sensible earthquakes in Tokyo.* The total numbers of the *sensible* earthquakes in Tokyo, which occurred during the different phases of the latitude variation, between 1895 and 1903, were as follows:—

{	With minimum latitude	111 earthquakes.	
	„ maximum „	69	„
Sum... ..			= $E_1 = 180$ „
{	With decreasing latitude	76	„
	„ increasing „	47	„
Sum			= $E_2 = 123$ „

These figures apparently indicate that the earthquakes of the kind under consideration occurred most frequently with the minimum latitude and least frequently with the increasing latitude. In reality, however, such was not the case. Thus the total numbers of the months included under the different phases were as follows:—

{	Minimum latitude	26 months	
	Maximum „	16	„
Sum			= $S_1 = 42$ „
{	Decreasing latitude	14	„
	Increasing „	14	„
Sum			= $S_2 = 28$ „

The ratios $\frac{E_1}{S_1}$ and $\frac{E_2}{S_2}$ are practically identical, being respectively 4·3 and 4·4; a result which seems to indicate that the frequency of the sensible earthquakes in Tokyo has no relation to the latitude variation.

5. *Earthquakes of area greater than 1000 square ri.* The numbers of recent Japan earthquakes of land area of disturbance¹⁾ greater than 1000 square ri, which happened during the different phases of

1) "Area of disturbance" of an earthquake means here the area within which the shaking was felt, or strong enough to be perceptible without instrumental aid.

the latitude variation, between 1895 and 1903, were as follows:—

{	With minimum latitude	49 earthquakes.	
	„ maximum „	29 „	
Sum			$E_1' = 78$ „
{	With decreasing latitude	36 „	
	„ increasing „	18 „	
Sum			$E_2' = 54$ „

The preponderance of the earthquakes in the epochs of the maximum and minimum latitude is here again only apparent; the total numbers of the months included under the different phases being as follows:—

{	Minimum latitude	12 months.	
	Maximum „	12 „	
Sum			$S_1' = 24$ „
{	Decreasing latitude	10 „	
	Increasing „	7 „	
Sum			$S_2' = 17$ „

The ratios $\frac{E_1'}{S_1'}$ and $\frac{E_2'}{S_2'}$ are equal to one another, being 3.3 and 3.2 respectively.

6. From what has been said in §§ 4 and 5, it seems that great destructive earthquakes in Japan have a marked tendency to occur in the epochs of the maximum and minimum latitude at Tokyo, a conclusion which is in harmony with the results already obtained by Prof. Milne (§ 2). On the other hand, the frequency of the small earthquakes or those whose areas of disturbance is, say, under 10,000 square *ri*, seems to have no particular relation to the latitude variation.

7. *Note on the long-period variations of seismic frequency.*

(a) Destructive earthquakes in Japan. Great seismic disturbances

happen sometimes singly or isolated but generally tend to occur in groups. Thus the 154 destructive earthquakes in Japan since the beginning of the 14th century may be more or less definitely divided into 41 groups, whose mean epochs recurred, on average, every $13\frac{1}{2}$ years.

(b) *Earthquakes in Kyōto.* Kyōto was the capital of the Empire during the 1070 years between 797 and 1867. The record of earthquakes in this city is therefore most complete, and includes 1318 shocks, of which 34 were destructive, 194 *strong*, and the remaining 1090 *slight*. Confining our attention to the two most disturbed epochs, namely, the 9th century and the time interval between the years 1340 and 1609, the seismic activity¹⁾ presents a series of fluctuations of periods, whose mean value is $6\frac{1}{2}$ years. Especially between the years 854 and 890 the variations were regular and had an average period of 6 years.²⁾ (See fig. 2.)

In connection with the periodicities of the seismic activity above considered it is interesting to note that, according to Dr. H. Kimura, who studied the latitude variation during the intervals between the years 1890 and 1902, the polar motion has a six years' period, the maximum deviations of the instantaneous pole having occurred in 1891 and 1897, and the minimum in 1894 and 1900.³⁾

The mean period of seismic activity at Kyōto is thus equal to that of the pole motion, while the mean epochs of the destructive earthquakes recur at intervals of nearly double the length.

8. *Earthquakes in Japan between 1885 and 1903.* For the sake of reference I give in the following table the numbers of earthquakes in the whole of Japan during the 19 years between 1885 and 1903, classified according to the land area of disturbance, and also to the

1) *Seismic activity* for each year is here the sum of the numbers of small, strong, and destructive earthquakes multiplied respectively with the coefficients 1, 2, and 2.

2) F. Omori: Notes on the Earthquake Investigation Committee Catalogue of Japanese earthquakes. Jour. Sc. Coll., Tōkyō Imp. Univ., Vol. XI.

3) H. Kimura: On the Six years' cycle of the polar motion during the interval 1891-1902. Astr. Nachr., No. 3932, Feb. 1904.

*intensity*¹⁾ of motion at the epicentre or at the nearest sea-coast in cases the latter was submarine. Some of the *slight* earthquakes were unfelt ones, which were, however, intense enough to be registered by ordinary Gray-Milne type seismographs.

JAPAN EARTHQUAKES IN RECENT YEARS.

Year.	Land area of disturbance. (in square ri)					Intensity.			Sum.
	<100	>100	>1,000	>5,000	>10,000	Strong.	Weak.	Slight.	
1885	309	143	28	2	0	—	—	—	482
1886	349	104	18	1	0	—	—	—	472
1887	349	97	34	3	0	—	—	—	483
1888	482	104	41	3	0	58	266	306	630
1889	767	117	44	2	0	51	290	589	930
1890	707	95	39	3	0	49	264	532	845
1891	1875	628	157	9	1	84	332	2164	2670
1892			26	4	0	85	242	1591	1918
1893			27	2	0	49	220	1267	1536
1894			25	12	5	65	335	2329	2726
1895			10	4	1	28	199	1200	1417
1896			15	20	3	56	273	1578	1907
1897			9	21	6	29	209	1493	1731
1898	1280	235	45	15	3	37	226	1384	1647
1899	1389	243	30	12	7	40	153	1562	1755
1900	1496	237	130	20	5	45	200	1643	1888
1901	1278	251	132	20	6	34	215	1361	1610
1902	1177	220	113	20	3	37	184	1267	1488
1903	1051	184	99	11	3	43	175	1131	1349

1) The *intensity* of non-destructive earthquakes is indicated as *strong*, *weak*, or *slight*. A *slight* shock is one which is very feeble and just sensible; a *weak* shock is one whose motion is well pronounced but not so severe as to cause general alarm; and finally a *strong* shock is one which is sufficiently severe to knock down some furniture, to cause people to run out of doors, etc

With respect to the above table, two things are to be remarked, namely, (1), that an enormous increase of earthquakes since 1891 is due to the after-shocks of the great earthquakes which took place in that and the subsequent years; and, (2), that a marked increase in the number of the earthquakes of area greater than 1000 square *ri* since 1900 is mainly due to the recent increase of the Gray-Milne type seismographs in the different parts of the country and to the consequent enlargement of the *area* of disturbance.

As stated before, the maximum deviations of the polar motion took place in 1891 and 1897, and also probably in 1903; and it is interesting to remark in this connection that the great Mino-Owari earthquake occurred in 1891, and the greatest number of earthquakes of land area larger than 5,000 square *ri* occurred in 1897, although the seismic activity was small in 1903.

A glance at the above table also indicates that the number of strong earthquakes (which include also violent and destructive ones) is not necessarily proportional to that of large earthquakes or those of great area of disturbance.

Tokyo. Aprii, 1904.



Note on the Annual Variation of the Height of Sea-level at Ayukawa and Misaki.

By

F. Omori, *Rigakushi, Rigakuhakushi,*

Member of the Imperial Earthquake Investigation Committee.

With Plate VII.

The present note, which is to be regarded as a supplement to my paper on the annual and diurnal variations of seismic frequency in Japan,¹⁾ treats of the comparison of the amount of fluctuation of the height of sea-level with that of the barometric pressure, at Ayukawa and Misaki. These two places are both situated on the Pacific coast of the Main Island; Ayukawa, in the province of Rikuzen, having been selected on account of its proximity to the origins of the submarine earthquakes so often disturbing the north-eastern part of the Island, while Misaki, in the province of Sagami, has been taken for the sake of comparison.

The following table, which has been deduced from the tide-gauge observations during the year 1902 at Ayukawa and Misaki, gives the mean monthly values of the distance between the sea surface and the datum line in the mareogram at each of the two places.

1) See the *Publications*, No. 8.

Month.	Distance between sea surface and datum line in the mareograph. ¹⁾	
	Ayukawa.	Misaki.
	metre.	metre.
January.	3.545	3.703
February.	3.666	3.832
March.	3.643	3.763
April.	3.621	3.729
May.	3.570	3.644
June.	3.495	3.661
July.	3.469	3.657
August.	3.482	3.606
September.	3.447	3.556
October.	3.494	3.584
November.	3.539	3.668
December.	3.509	3.575

The results contained in the above table are illustrated in fig. 1, which shows that the variation of the height of the sea level at Ayukawa was nearly similar to that at Misaki.

The following table gives the mean monthly relative heights of the sea-level at Ayukawa and Misaki, deduced from the preceding together with the mean monthly barometric pressures during the same year deduced from the mean of the observations at the meteorological observatories of Ishinomaki and Yokosuka; the two latter places being respectively near to Ayukawa and Misaki.

Month.	Mean height of sea-level.			Mean barometric pressure (reduced to sea-level and 0°C.)
	Misaki.	Ayukawa.	Mean	
	mm	mm	mm	mm mm
January.	129	121	125	700 + 61.3
February.	0	0	0	64.5
March.	69	23	46	62.2
April.	103	45	74	60.2

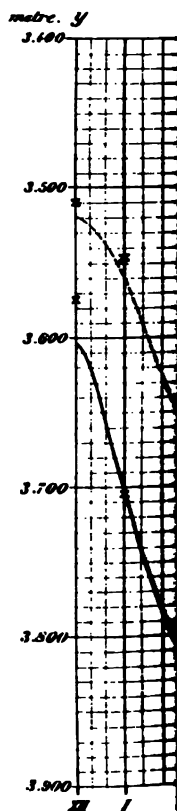
1) The figures in the table were furnished by the Survey Department of the General Staff.

Month.	Mean height of sea-level.			Mean barometric pressure (reduced to sea-level and 0°C.)
	Misaki.	Ayukawa.	Mean.	
	mm	mm	mm	mm mm
May.	188	96	142	700+59.4
June.	171	171	171	56.4
July.	175	197	186	56.2
August.	226	184	205	58.8
September.	276	219	248	58.7
October.	248	172	210	64.1
November.	164	117	141	65.5
December.	257	157	207	61.0

From fig. 2, which graphically illustrates the results contained in the above table, it will be seen that the curve of the annual variation of the barometric pressure is nearly opposite to that of the height of sea-level. Further, the annual fluctuation of the mean monthly barometric pressure was 9.3 mm, which corresponds to $9.3 \times 13.6 = 126$ mm height of water. On the other hand, the annual fluctuations of the height of sea-level were 276 and 219 mm at Misaki and Ayukawa respectively. At these places, therefore, the fluctuation of the height of sea-level is opposite to, and nearly double, that of the atmospheric pressure. In other words, the sea bottom is subjected to a greater *total* pressure in the summer months than in Feb., March, and April, the difference between the maximum and minimum total pressure being nearly equal to that of the annual amount of fluctuation of the monthly mean barometric height. Such is probably true of the whole Pacific coasts of the Japanese islands.

The increase in the height of sea-level in summer months as above described is to be explained partly by the fall in summer of the atmospheric pressure over Japan and the neighbouring seas, and partly by the presence of a high pressure area on the northern Pacific in the vicinity of the Aleutian islands; the surface of the ocean being consequently thrown into a curve form, such that the surface of the water is depressed beneath the high pressure centre and elevated along

the coasts of the Japanese islands. Similarly the decrease of the height of sea-level in winter months is to be explained by the rise of the atmospheric pressure over Japan and the presence of a low pressure area on the northern Pacific. This probably explains the occurrence in summer and in winter respectively of the maximum and minimum seismic frequencies at those places which are shaken principally by earthquakes of sub-oceanic origin.



$y = \text{Mean}$
of the



Note on the Lunar-daily Distribution of Earthquakes.¹⁾

By

F. Omori, *Rigakushi, Rigakuhakushi*,

Member of the Imperial Earthquake Investigation Committee,

With Plates VIII and IX.

1. INTRODUCTION. The relations between earthquake frequency and the moon's position were discussed by several seismologists since the middle of the 19th century. The following is a brief summary of the more important investigations in recent years.

M. de Montessus de Ballore²⁾ who treated a vast earthquake catalogue, has obtained a wholly negative result. Thus, dividing the lunar day of 24 h 50 m into eight parts, of which the middle of the first corresponds to the time of the upper culmination, he finds the following earthquake distributions³⁾:—

I eighth	5579 earthquakes.
II	5558
III	5611
IV	5508
V	5802
VI	5564
VII	5571
VIII	5662

1) Translation, with some additions, of an article by the Author published in the *Reports (Japanese)* of the Imp. Earthq. Inv. Com., No. 32, 1900.

2) *Archives des Sciences Physiques et Naturelles*, Tome XXII, 1889.

3) *Trans. Seism. Soc.*, Vol. XV.

These figures are quoted from Dr. C. G. Knott's paper entitled: *M. de Ballore's calculations on earthquake frequency*¹⁾. He remarks that it is impossible to base any definite conclusion as to the lunar-daily periodicity in earthquakes on such numbers as these, the ratio of the maximum to the minimum being 105 : 100.

The most important of the recent investigations on the relation between earthquake frequency and the position of the moon is that by Dr. C. G. Knott, who examined the Japan earthquakes contained in Prof. Milne's great Catalogue (*Seis. Jour. of Japan*, Vol. IV), and arrived, amongst others, at the following results²⁾: — (1) Earthquake frequency is subject to a periodicity associated with the lunar day; (2) The lunar half-daily period is relatively prominent, and its phase falls regularly in relation to the time of the meridian passage of the moon.

2. In the discussion of the lunar influence on earthquakes, the after shocks of a great earthquake may be supposed as furnishing the best materials for investigation, on the following two accounts:—(1) after-shocks are probably no other than the removal of the residual unstable or weak points at the disturbed tract about the focus of a great seismic disturbance, which must be particularly sensitive to the action of external agencies; (2) these shocks are mostly small local shakings whose origins are near to one another. From these considerations, I have taken, by way of trial, the after-shocks at Nagoya of the Mino-Owari earthquake of 1891, and those at Nemuro of the Hokkaido earthquake of 1894; and for the sake of comparison, ordinary earthquakes at Tokyo. The earthquake observations at Nagoya, Nemuro, and Tokyo, whose distribution in the lunar-day considered in the following §§, have all been made instrumentally by means of the Gray-Milne type seismographs.

3. LUNAR DAY. The lunar day is divided into 24 hours, the 0 hour corresponding with the moon's upper culmination for Tokyo.

1) *Trans. Seism. Soc.*, Vol. XV.

2) Prof. C. G. Knott: *On Lunar Periodicities in Earthquake Frequency*. *Proc. Royal Soc. London*, Vol. LX, 1897.

The times of occurrence of the earthquakes at Nagoya and Nemuro, as well as those at Tokyo, have all been referred to the lunar time for the last named place. This will, however, lead to no great inaccuracy, as the longitudes at these three places are not much different from each other, being respectively $136^{\circ} 55'$, $145^{\circ} 35'$, and $139^{\circ} 45' E$.

4. AFTER-SHOCKS AT NAGOYA. The great Mino-Owari earthquake took place on Oct. 28, 1891, at about 6 h 37 m a.m. The number of the after-shocks observed at the meteorological observatory of Nagoya till the end of the year 1899 was 1854. In order to avoid the effect of the rapid decrease in the seismic frequency at the commencement, let us exclude the observations within the two weeks immediately after the initial earthquake. Thus we obtain 1270 shocks for the time interval between Nov. 11, 1891, and Dec. 31, 1899, whose lunar-daily distribution is as follows.

TABLE I. LUNAR-DAILY DISTRIBUTION OF 1270
EARTHQUAKES AT NAGOYA.
(Nov. 11th, 1891-Dec. 31st, 1899.)

Year. Lunar hour	1891	1892	1893	1894	1895	1896	1897	1898	1899	Sum.	
										Hourly.	3-hourly.
h h											
0-1	9	7	4	8	4	8	2	3	1	46	174
1-2	11	16	2	16	9	4	0	3	0	61	
2-3	15	7	5	17	10	2	2	3	6	67	
3-4	11	10	5	11	8	3	0	1	2	54	178
4-5	10	10	4	22	3	10	4	0	0	63	
5-6	18	11	1	12	7	1	8	0	3	61	
6-7	14	12	4	11	2	4	3	1	1	52	156
7-8	13	9	4	14	2	3	6	3	3	57	
8-9	10	8	5	11	4	3	2	2	2	47	
9-10	4	8	6	11	4	6	3	3	4	49	148
10-11	5	14	6	14	11	0	1	0	1	52	
11-12	7	8	6	9	9	3	3	1	1	47	
12-13	8	9	11	14	5	6	5	3	2	63	162
13-14	14	9	2	13	5	3	1	1	0	48	
14-15	10	5	2	14	2	7	4	3	4	51	
15-16	8	7	5	6	11	12	5	1	2	57	168
16-17	15	7	10	6	9	6	5	1	1	60	
17-18	9	7	7	8	5	7	3	3	2	51	
18-19	11	5	4	15	3	3	1	4	0	46	143
19-20	10	6	2	9	3	4	1	0	3	38	
20-21	18	7	8	9	6	3	4	2	2	59	
21-22	13	9	2	9	7	1	0	2	1	44	141
22-23	14	5	3	16	7	4	0	1	1	51	
23-24	19	0	9	1	7	6	2	1	1	46	
Sum.	279	196	117	276	143	109	65	42	43	1270	
Mean.....53...159											

The results in Table I are illustrated in figs. 1 and 4, x being the time and y the corresponding hourly number of earthquakes.¹⁾

Hourly distribution. The principal maximum and minimum hourly

1) The curve is drawn free-hand through the mean positions of every two successive points representing the relation between x and y . This method of curve drawing has been used in the case of the other diagrams.

numbers of 67 and 38 occurred respectively between the 2nd and 3rd hours, and between the 19th and 20th hours :

$$\begin{aligned} \text{Greatest hourly earthquake number} &= a = 67 ; \\ \text{Smallest} \quad , , \quad , , \quad , , &= b = 38 ; \\ \text{Mean} \quad , , \quad , , \quad , , &= c = 53 ; \\ &a - b = d = 29 ; \\ &\frac{d}{c} = e = 55 \% . \end{aligned}$$

The second maximum (=63) and minimum (=47) occurred respectively between the 12th and 13th hours, and between the 8th and 9th hours.

3-Hourly distribution. The curve, which is drawn by taking the earthquake numbers every 3 hours (fig. 4), indicates clearly two maxima and two minima. The principal maximum and minimum numbers of 178 and 141 occurred respectively between the 3rd and 6th hours and between the 21st and 24th hours :—

$$\begin{aligned} \text{Greatest 3-hourly earthquake number} &= A = 178 ; \\ \text{Smallest} \quad , , \quad , , \quad , , &= B = 141 ; \\ \text{Mean} \quad , , \quad , , \quad , , &= C = 159 ; \\ &A - B = D = 37 ; \\ &\frac{D}{C} = E = 23 \% . \end{aligned}$$

The 2nd maximum (=168) and minimum (=148) occurred respectively between the 15th and 18th hours, and between the 9th and 12th hours.

The symbols $a, b, c, d, e, A, B, C, D, E$, have in the cases of Nemuro and Tokyo earthquakes considered next the same meaning as in the present §.

5. NEMURO AFTER-SHOCKS. The Hokkaido earthquake took place on March 22, 1894, at 7h 56m p.m. The after-shocks recorded at the Meteorological Observatory of Nemuro till the end of 1899 was 1057. Excluding the shocks which happened during the first three days, to avoid the effect of the rapid decrease at the commencement, there were

in the time interval between March 25th, 1894, and Dec. 31st, 1899, 799 earthquakes, whose lunar daily distribution is as in Table II.

TABLE II. LUNAR-DAILY DISTRIBUTION OF 799
EARTHQUAKES AT NEMURO.
(March 25th, 1894—Dec. 31st, 1899.)

Year. Lunar hour	Year.						Sum.	
	1894	1895	1896	1897	1898	1899	Hourly.	3-hourly.
h h								
0-1	21	8	4	2	2	0	37	106
1-2	20	8	7	2	1	2	40	
2-3	18	1	1	2	2	5	29	
3-4	20	7	4	2	1	5	39	117
4-5	25	8	5	5	2	2	47	
5-6	14	6	1	2	2	2	31	
6-7	17	7	5	2	5	4	40	92
7-8	11	2	4	1	1	1	20	
8-9	17	7	3	3	1	1	32	
9-10	14	4	2	5	3	3	31	98
10-11	17	7	5	4	1	1	35	
11-12	21	3	4	2	1	1	32	
12-13	17	10	3	4	4	1	39	107
13-14	23	4	5	2	1	1	36	
14-15	14	7	2	2	2	5	32	
15-16	21	5	3	2	1	4	36	95
16-17	14	4	2	3	3	3	29	
17-18	17	2	4	4	1	2	30	
18-19	19	5	7	1	0	1	33	98
19-20	13	4	1	4	3	7	35	
20-21	25	1	2	1	0	1	30	
21-22	17	9	3	4	0	3	36	86
22-23	9	2	2	3	2	3	21	
23-24	12	6	4	0	3	4	29	
Sum.	423	127	83	62	42	62	799	
Mean 33 . . . 100								

Hourly distribution. According to fig. 2, the principal maximum and minimum hourly numbers of 47 and 20 occurred respectively between the 4th and 5th hours, and between the 7th and 8th hours:

$$\begin{aligned}
 a &= 47 \text{ earthquakes.} \\
 b &= 20 \quad \text{,,} \\
 c &= 33 \quad \text{,,} \\
 a - b &= d = 27 \quad \text{,,} \\
 \frac{d}{c} &= e = 82 \%
 \end{aligned}$$

The 2nd maximum and minimum of 39 and 21 occurred respectively between the 12th and 13th hours, and between the 22nd and 23rd hours.

3-Hourly distribution. According to fig. 5, which shows the 3-hourly distribution of the earthquakes, there were two maxima and two minima. The principal maximum and minimum numbers of 117 and 86 occurred respectively between the 3rd and 6th hours, and between the 21st and 24th hours:—

$$\begin{aligned}
 A &= 117 \text{ earthquakes.} \\
 B &= 86 \quad \text{,,} \\
 C &= 100 \quad \text{,,} \\
 A - B &= D = 31 \quad \text{,,} \\
 \frac{D}{C} &= E = 31 \%
 \end{aligned}$$

The 2nd maximum and minimum of 107 and 92 occurred respectively between the 12th and 15th hours, and between the 6th and 9th hours.

6. TOKYO EARTHQUAKES. The lunar-daily distribution of the 1462 earthquakes observed at the Central Meteorological Observatory during the 12 years between Jan. 1888 and Dec. 1899 is given in Table III.

TABLE III. LUNAR-DAILY DISTRIBUTION OF 1462
EARTHQUAKES AT TOKYO.

(Jan. 1888—Dec. 1899.)

year Lunar hour.													Sum.	
	1888	1889	1890	1891	1892	1893	1894	1895	1896	1897	1898	1899	Hourly.	3-hourly.
h h														
0—1	4	3	6	7	4	2	9	9	13	7	5	2	71	190
1—2	4	4	2	5	6	4	1	10	6	5	5	4	56	
2—3	4	6	7	3	4	3	2	5	10	7	4	8	63	
3—4	6	5	1	4	6	3	6	3	9	4	5	6	58	184
4—5	6	5	4	4	2	0	7	4	9	14	9	4	68	
5—6	3	3	5	3	3	3	3	4	12	5	4	10	58	
6—7	2	9	8	6	5	3	6	4	9	8	6	2	68	185
7—8	8	8	3	4	7	3	3	5	5	4	8	3	61	
8—9	3	4	3	4	4	3	3	5	9	2	8	8	56	
9—10	3	2	5	4	5	1	4	5	8	8	10	4	59	167
10—11	2	2	4	6	4	1	4	5	13	7	6	1	55	
11—12	5	3	4	6	2	3	4	2	8	7	5	4	53	
12—13	4	7	3	7	7	6	6	5	9	5	9	4	72	189
13—14	3	8	3	3	3	0	3	5	10	5	8	3	54	
14—15	6	3	2	5	2	4	5	5	10	9	7	5	63	
15—16	5	4	7	7	4	0	4	6	12	11	7	4	71	186
16—17	4	5	2	3	3	1	1	4	4	10	3	6	46	
17—18	4	9	1	5	5	4	3	4	14	6	7	7	69	
18—19	2	3	3	1	3	5	4	10	9	7	4	8	59	188
19—20	7	8	6	6	3	0	5	4	11	5	5	5	65	
20—21	5	3	3	5	3	2	6	6	8	7	8	8	64	
21—22	3	2	2	4	2	4	5	10	12	6	4	8	62	173
22—23	4	5	6	7	4	2	1	4	5	4	3	8	53	
23—24	4	2	3	14	1	4	6	7	5	5	3	4	58	
	101	113	93	123	92	61	101	131	220	158	143	126	1462	

Mean. 61.....183

Hourly distribution. According to fig. 3, the principal maximum and minimum hourly earthquake numbers of 72 and 46 occurred respectively between the 12th and 13th hours, and between the 16th and 17th hours :—

 $a = 72$ earthquakes $b = 46$ „

$$\begin{aligned}
 c &= 61 \text{ earthquakes} \\
 a - b &= d = 26 \quad ,, \\
 \frac{d}{c} &= e = 43 \%
 \end{aligned}$$

The 2nd maximum of 71 occurred between the 0 and 1st hours, and the 2nd minimum of 53 between the 11th and 12th hours and also between the 22nd and 23rd hours.

3-Hourly distribution. The curve of the 3-hourly distribution (fig.6) indicates clearly a 12-hours period. The maximum and minimum numbers of 190 and 167 occurred respectively between the 0 and 3rd hours, and between the 9th and 12th hours:—

$$\begin{aligned}
 A &= 190 \text{ earthquakes} \\
 B &= 167 \quad ,, \\
 C &= 183 \quad ,, \\
 A - B &= D = 23 \quad ,, \\
 \frac{D}{C} &= E = 13 \%
 \end{aligned}$$

The 2nd maximum and minimum of 189 and 173 occurred respectively between the 12th and 15th hours, and between the 21st and 24th hours.

7. SUMMARY OF RESULTS. The results obtained in the preceding three §§ may be summarized as follows.

Hourly distribution. The curves of the hourly earthquake distribution for the three places are similar to one another, each indicating two maxima, of which the 1st occurred between the 0 and 5th hours, and of which the 2nd occurred in all the three cases between the 12th and 13th hours. In the case of the Tokyo earthquakes the two maxima were nearly equal to one another; while in the cases of Nagoya and Nemuro earthquakes, the 1st maximum was somewhat greater than the 2nd. The occurrence of the two seismic maxima, at a mean interval of 12 hours, and approximately at, or a little after, the meridian passages of the moon, may probably be due to the stress in the earth's crust caused by the direct attraction of the moon.

The dotted lines in figs. 1, 2 and 3, showing the mean variation of the earthquake frequency, indicate in each case, two maxima, of which the 1st occurred between the 7th and 12th hours, and the 2nd between the 19th and 23rd hours.

It is hereby to be remarked that almost the total number of the earthquakes at Nemuro and Nagoya were small local shocks, whose origins were, in the two cases, totally different. Further, the Nemuro earthquakes were entirely of submarine origin, and Nagoya earthquakes mostly of inland origin; while the Tokyo earthquakes, whose origins were different from those at the two above places, were partly submarine and partly inland. Notwithstanding these differences in the origins of earthquakes the lunar-daily distribution of earthquakes at the three places were alike to one another. The values of c , or the amount of fluctuation of the hourly number of earthquakes, for Nagoya, Nemuro, and Tokyo, were respectively 55, 82, and 43%, giving an average of 60%.

8. TIDES. The relation between earthquakes and the position of the moon must be a complicated one, as, besides the direct stress caused by the moon in the earth's crust, there we have also to deal with the effect of the tides, for which the times of high and low waters are considerably different in various portions of the coasts of the Japanese Islands. At Reigan-jima, Tokyo, the high water occurs from 5 h to 6 h 20 m after the meridian passage of the moon. The times of the high water at some places along the Pacific and Japan sea coasts, referred to that at Reigan-jima, are as in the following table; being positive (+) when additive, and negative (−) when subtractive.

Place.	Time of High water.	Place.	Time of High water.
Kuwana.	+0h 37m	Yokohama.	−0h 01m
Hyogo.	+1 34	Ishinomaki.	−1 16
Osaka.	+2 01	Hakodate.	−1 03
Shimonoseki.	+3 06	Niigata.	−3 01
Nagasaki.	+1 56	Fushiki.	−2 57

From the above table, it will be seen that the times of the high water at the different places on the Japanese coasts are 2 to $9\frac{1}{2}$ hours after the meridian passage of the moon. The fluctuations in the seismic frequency shown in figs. 1, 2, and 3, may entirely, or partly, be due to the tidal motion of sea waters. (See also § 9.)

9. *3-Hourly variation.* The curves of the 3-hourly seismic variation at the three places (figs. 4, 5, and 6) are approximately identical with one another, each indicating two maxima and two minima. The two maxima occurred respectively between the 0 and 6th hours, and between the 12th and 18th hours; the 1st maximum being somewhat greater than the 2nd. The two minima occurred respectively between the 6th and 12th hours, and between the 21st and 24th hours. The values of the ratio E' , or the amount of the fluctuation of the 3-hourly seismic frequency, were for Nagoya, Nemuro and Tokyo, respectively 23, 31, and 13%, giving an average of 22%.

10. The conclusions above obtained for the three places of Nagoya, Nemuro and Tokyo, may be different from those for other places. It is, for instance, quite possible that for some places the lunar-daily distribution of earthquakes indicates only a single maximum and a single minimum. The discussion of earthquakes observed at Gifu, Kumamoto, Kagoshima, Ishinomaki, Utsunomiya, etc., will form the subject of another note.

11. COMPARISON OF THE LUNAR AND BAROMETRIC EFFECTS ON THE SEISMIC FREQUENCY. Let us compare the lunar effect discussed above with the effect of the barometric pressure on the diurnal seismic frequency at the same three places. In the *Publications*, No. 8, there are tables showing diurnal distributions of 1851, 991, and 2208 earthquakes observed at Nagoya, Nemuro and Tokyo respectively. From these tables, as well as from those given in §§ 4, 5 and 6, I have constructed the following, showing for each place the excess of the different hourly earthquake numbers over the least.

TABLE IV. LUNAR-DAILY AND DIURNAL VARIATIONS OF SEISMIC FREQUENCY.

Lunar hour.	MOON'S EFFECT. (Lunar-daily seismic variation.)					Hour.	BAROMETRIC EFFECT. (Diurnal seismic variation.)				
	Nagoya.	Nemuro.	Tokyo.	Sum.	Sum— Minimum.		Nagoya.	Nemuro.	Tokyo.	Sum.	Sum— Minimum.
						a.m.					
0—1	46	37	71	154	29	0—1	99	39	92	233	64
1—2	61	40	56	157	32	1—2	117	40	81	238	72
2—3	67	29	63	159	34	2—3	96	40	90	226	60
3—4	54	39	58	151	26	3—4	101	50	85	236	70
4—5	63	47	68	178	53	4—5	103	50	71	224	58
5—6	61	31	58	150	25	5—6	82	48	87	217	51
6—7	52	40	68	160	35	6—7	61	44	95	200	31
7—8	57	20	61	138	13	7—8	60	50	92	202	36
8—9	47	32	56	135	10	8—9	82	44	96	222	56
9—10	49	31	59	139	14	9—10	67	37	113	217	51
10—11	52	35	55	142	17	10—11	57	43	93	193	27
11—12	47	32	53	132	7	11—12	82	53	84	219	53
						p.m.					
12—13	63	39	72	174	49	0—1	55	41	79	175	9
13—14	48	36	54	138	13	1—2	79	26	91	196	30
14—15	51	32	63	146	21	2—3	56	25	85	166	0
15—16	57	36	71	164	39	3—4	72	45	104	221	55
16—17	60	29	46	135	10	4—5	65	44	97	206	40
17—18	51	30	69	150	25	5—6	78	42	81	201	35
18—19	46	33	55	138	13	6—7	55	38	89	182	16
19—20	38	35	65	138	13	7—8	75	43	93	211	45
20—21	59	30	64	153	28	8—9	67	41	104	212	46
21—22	44	36	62	142	17	9—10	79	41	100	220	54
22—23	51	21	53	125	0	10—11	85	30	107	222	56
23—24	46	29	58	133	8	11—12	81	37	99	217	51
Sum	1270	799	1462	3531	531	Sum	1854	991	2208	5053	1069

Let N , S , S_1 , and S_2 denote, for the lunar-daily distribution, the following quantities:—

N = Hourly number of earthquakes;

S = Total earthquake number;

$$S_1 = 24 \times b ;$$

$$S_2 = S(N - b) = S - S_1 ;$$

b denoting the minimum hourly earthquake number, as in §§ 4, 5 and 6. Further let the symbols b' , N' , S' , S_1' , and S_2' denote the corresponding quantities for the diurnal distribution of earthquakes. Then the results contained in the above table may be summarized as in the two following ones.

Lunar-daily Earthquake Distribution.

Place.	S	$S_1 = 24 \times b.$	$S_2 = S - S_1$	Ratio, $\frac{S_2}{S_1}$	Ratio, $\frac{S_2}{S}$
Nagoya.	1270	912	358	0.39	0.28
Nemuro.	799	480	319	0.66	0.40
Tokyo.	1462	1104	358	0.33	0.25
3 places taken together.	3531	3000	531	(mean) 0.46	(mean) 0.31

Diurnal Earthquake Distribution.

Place.	S'	$S_1' = 24 \times b'.$	$S_2' = S' - S_1'$	Ratio, $\frac{S_2'}{S_1'}$	Ratio, $\frac{S_2'}{S'}$
Nagoya.	1854	1320	534	0.40	0.29
Nemuro.	991	600	391	0.65	0.39
Tokyo.	2208	1704	504	0.30	0.23
3 places taken together.	5053	3984	1069	(mean) 0.45	(mean) 0.30

From the above two tables, we see that, for each of the three places, the ratios $\frac{S_2}{S_1}$ and $\frac{S_2}{S}$ are very nearly equal respectively to the ratios $\frac{S_2'}{S_1'}$ and $\frac{S_2'}{S'}$, which shows that in the diurnal and lunar-daily seismic variations the moon's effect is approximately equal to that of the barometric pressure. This fact admits of a simple explanation, provided the *lunar effect* be considered not as the effect of the moon's

direct attraction, but as the effect due to the weight of the sea waters in the tidal motion. Thus, according to my note on the annual variation of the height of sea-level,¹⁾ the total change of pressure at the sea bottom off the Pacific coast of the Main Island seems to be opposite in sense, but equal in amount, to that of the barometric pressure on land.

The numbers S_2 and S_2' , which may be assumed respectively as the aggregate amount of the lunar and barometric effects on the lunar-daily and diurnal seismic variations are as follows:

For Nagoya: $S_2 + S_2' = 28 + 29 = 57 \%$

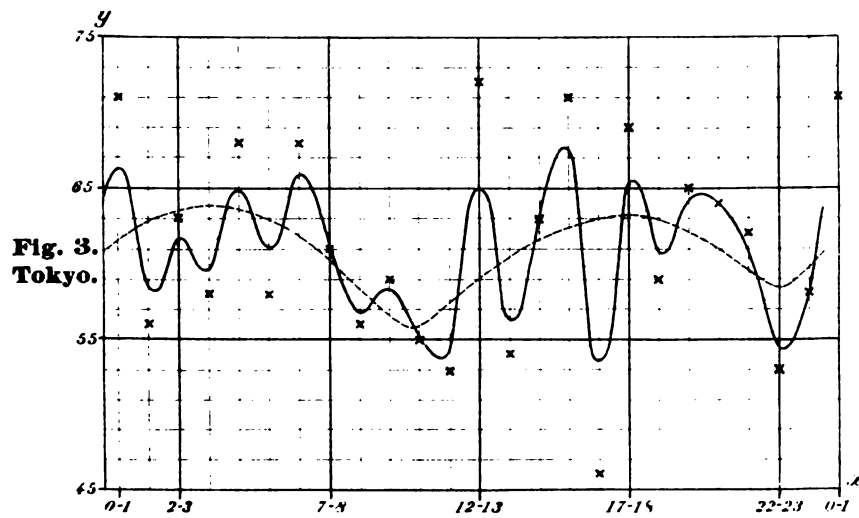
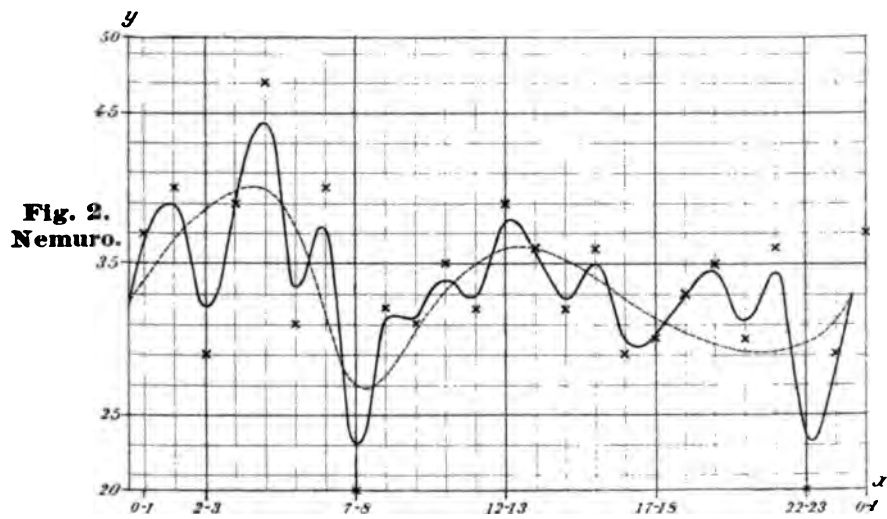
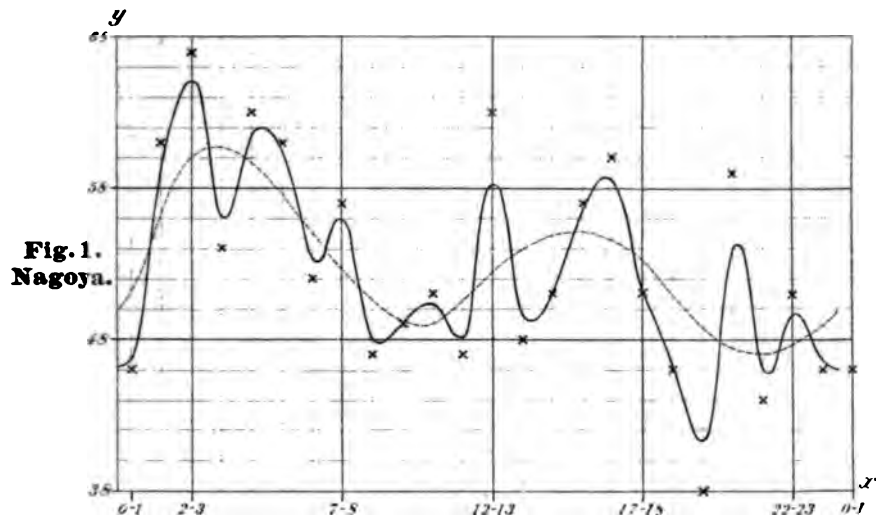
„ Nemuro: „ = $40 + 39 = 79$ „

„ Tokyo : „ = $25 + 23 = 48$ „

It thus seems that a considerable proportion of earthquakes, from some 50 to 80 %, are caused, or accelerated to occur, by the agencies of the atmospheric pressure and the moon's influence or tidal stress.

1) This volume, pp. 24-26.

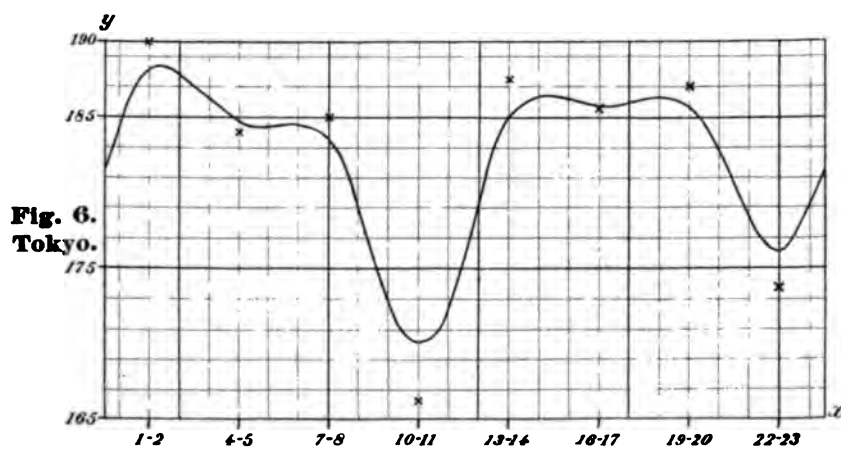
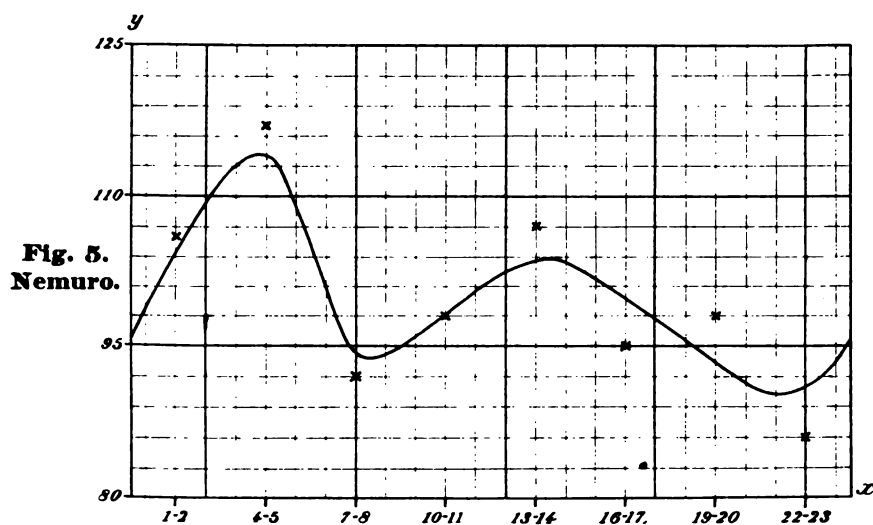
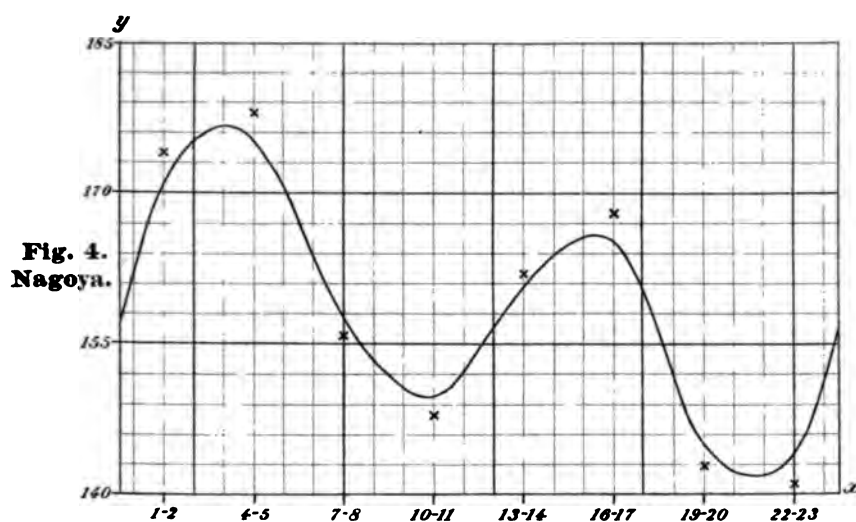
Lunar-daily distribution of Earthquakes.



x =Time (lunar hour).

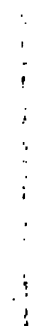
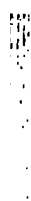
y =Hourly (lunar) number of earthquakes.

Lunar-daily distribution of Earthquakes.



x = Time (lunar hour).

y = 3-hourly (lunar) number of earthquakes.



Synodic-monthly Variation of Seismic Frequency in Japan.

By

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Extraordinary Member of the Imperial Earthquake
Investigation Committee.

With Plates X-XVII.

I. Introduction.

1. The relations between the periodic fluctuations of earthquake frequency and the external agencies, which have already been discussed by several seismologists, may be supposed to be most distinctly shown when the earthquakes treated are confined into certain localities, as a few recent investigators have done.

2. Dr. Omori was the first to discuss fully the after-shocks of great earthquakes, the advantage in considering these shocks with respect to the problem above mentioned being that they are numerous and ought to be readily affected by external agencies. Thus treating, besides the 1462 earthquakes observed in Tōkyō, 1270 after-shocks of the great Mino-Owari earthquake of 1891, and 799 after-shocks of the Nemuro earthquake of 1894, he arrived at the conclusion that earthquakes occurred most frequently within a few hours after the meridian passages of the moon and least frequently about 6 hours later¹, the result being similar to that obtained by Dr. Knott² who made an analytical study of 7000 Japanese earthquakes contained in Professor Milne's Catalogue. Dr. Oldham's result of the discussion of 1274

1. This volume, pp. 27-40.

2. Proceedings of the Royal Society of London, vol. VX.

after-shocks of the great Assam earthquake of 1897 is that the shocks were most frequent between 10 and 11 p.m., and again between 6 and 7 a.m.¹ This is very similar to the conclusion arrived at by Dr. Omori, who, treating 18279 seismic observations at 26 Meteorological Stations in Japan obtained many important results, from which it appears that the seismic frequency is more affected by the barometric pressure than by the direct influence of the sun such that the curve of diurnal seismic frequency follows closely that of barometric pressure, large seismic numbers corresponding to high pressures.²

3. An interesting study on the distribution of seismic occurrences with respect to the relative position of the sun and moon has been undertaken also by Dr. Knott, who arrived at the conclusion that the seismic frequency reaches its maximum at the times of the conjunction and opposition of the sun and moon, and its minimum at the times of quadrature.³

4. The treatment, similar to that last mentioned, having been very easy with respect to the Japanese historical earthquakes contained in our Committee's Catalogue, in which the dates of occurrences are given both in Japanese synodic and European calendars, I have taken up the problem again and found that the maximum seismic frequency occurred not only at the times of the conjunction and opposition of the sun and moon, but also at the times of quadrature. This latter conclusion is found to be the same in the case of the recent Japanese earthquakes observed at the different Meteorological Stations. A detailed account is given in the following Chapters.

II. Synodic-daily distribution of the Japan historical earthquakes.

5. The Earthquake Investigation Committee Catalogue contains

-
1. Journal of the Asiatic Society of Bengal, vol. LXXXI.
 2. Publications of the Imp. Earthquake Inv. Comm. in Foreign Languages, No. 8.
 3. Dr. Knott: On Lunar Periodicities in Earthquake Frequency. Proceedings of the Royal Society of London.

a list of 1898 earthquakes, a large disturbance and its after-shocks being reckoned as a single number.¹ These earthquakes are classed according to the intensity as *destructive*, *strong*, or *small*, each of which corresponds approximately to *violent*, *strong*, and *weak* or *slight* of the scale adopted by the Central Meteorological Observatory.

6. A few words must be said of Japanese synodic calendar. The first day of the lunar month is approximately the time of the conjunction of the sun and moon, while the 16th is the time of opposition. As a complete synodic month is almost equal to 29.53 mean solar days, months consisting of 29 and 30 days come alternately, or in other words the 30th day numbers 53 % of any other day during a sufficiently long period. Hence I multiplied, for the use of drawing the frequency curve, the factor $100/53$ into the seismic number in the 30th, in order to raise the datum of this day into equal weight as in the other days.

7. Let us now turn our attention to Tables I and II. The first of these relates to the earthquakes all over Japan, while the second relates to the 1317 earthquakes recorded in Kyoto.² The column with the heading "sum with weight" is *filled up* with the sums of small, strong, and destructive earthquakes of successive days each multiplied with the factors 1, 2, and 3 respectively. The last column with the heading "reduced" consists of numbers of the corresponding days in the former column divided by the daily average of the numbers in that column.

1-2. In a few cases, date of occurrences is unknown.

TABLE I.

SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
RECORDED IN JAPAN, BETWEEN 416 AND 1860, A. D.

Synodic day.	Small.	Strong.	Destructive.	Sum without weight.	Sum with weight.	Reduced.
1	66	14	8	88	118	1.40
2	71	5	5	81	96	1.14
3	55	9	5	69	88	1.04
4	45	11	5	61	82	0.97
5	50	8	7	65	87	1.03
6	46	12	5	63	85	1.01
7	55	8	12	76	108	1.28
8	37	11	3	51	68	0.81
9	39	8	8	55	71	0.84
10	44	10	4	58	76	0.90
11	45	8	3	56	70	0.83
12	43	6	12	61	91	1.08
13	70	8	2	80	92	1.09
14	54	10	6	70	92	1.09
15	48	6	8	62	84	1.00
16	55	7	6	68	87	1.03
17	48	10	2	60	74	0.88
18	50	9	3	62	77	0.91
19	47	9	5	61	80	0.95
20	33	9	7	49	72	0.85
21	41	11	6	58	81	0.96
22	45	11	5	61	82	0.97
23	47	1	11	59	82	0.97
24	46	11	8	65	92	1.09
25	56	9	7	72	95	1.13
26	37	7	11	55	84	1.00
27	46	14	6	66	92	1.09
28	39	4	5	48	62	0.74
29	44	12	4	60	80	0.95
30	24	4	3	31	77	0.91
Sum.	1427	262	182	1871	2525	—

TABLE II.

SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
RECORDED AT KYOTO, BETWEEN 416 AND 1860, A. D.

Synodic day.	Slight.	Strong.	Large.	Sum without weight.	Sum with weight.	Reduced.
1	41	10	1	55	67	1.26
2	51	4	1	56	62	1.16
3	42	4	0	46	50	0.94
4	35	10	2	47	61	1.14
5	40	7	1	48	57	1.07
6	33	8	3	44	61	1.14
7	45	6	2	53	63	1.18
8	22	7	1	30	39	0.73
9	31	8	2	41	56	1.05
10	32	4	0	36	40	0.75
11	38	3	1	42	47	0.88
12	35	2	5	42	54	1.01
13	50	7	0	57	64	1.20
14	41	9	1	51	63	1.18
15	34	4	2	40	48	0.90
16	42	5	1	48	55	1.03
17	36	7	0	43	50	0.94
18	40	5	2	47	56	1.05
19	33	6	0	39	45	0.84
20	29	5	2	36	45	0.84
21	34	6	0	40	46	0.86
22	34	9	3	46	61	1.14
23	39	0	1	40	42	0.79
24	34	8	5	47	65	1.22
25	45	8	1	54	64	1.20
26	28	7	1	36	45	0.84
27	37	12	0	49	61	1.14
28	31	2	0	33	35	0.66
29	34	10	2	46	60	1.12
30	13	3	1	17	42	0.79
Sum	1085	186	41	1312	1604	—

8. The *weighted* numbers of earthquakes of successive days, when drawn in curves (figs. 1-2), indicate two distinct pairs of maxima on the 1st and 14th, and the 7th and 24th. The method of drawing curves here adopted is as follows:—Let x represent the synodic days, and y the actual seismic number of the corresponding day. Marking down on a section paper so many points ($\times$) corresponding to the different sets of x and y , the curve is obtained by drawing a continuous free-hand line, which passes through the mean positions of every two consecutive points ($\times$) tangentially to the broken line connecting directly the points themselves.¹

9. As regards the causes of the two pairs of maxima, the first is probably due to the combined tidal effort of the sun and moon, and the second to the resultant of tidal and barometric pressures. For the explanation, the reader is referred to Chapter IV.

III. Synodic-daily distribution of the seismic observations at the different Meteorological Stations.

10. I shall now proceed to discuss the distribution of earthquakes observed at the different Japanese Meteorological Stations. As regards the full description of the observations at these stations, the reader is referred to Dr. Omori's paper on "annual and diurnal variations of seismic frequency in Japan."² As the monthly frequency is decidedly affected by the after-shocks of a certain large earthquake, I excluded them together with those earthquakes which occurred within a complete synodic month after that earthquake. For this reason, the observations at Nemuro, Gifu, Nagoya, etc., which have been taken into consideration were considerably reduced in number. The exclusions are given in Table III, which besides gives the observations at the 22 Meteorological Stations. My examination relates also to the obser-

1. See Dr. Omori: Publications of the Imp. Earthquake Inv. Comm. in Foreign Languages, No. 8.

2. Loc. cit.

vations at 8 other stations, but, the materials in these cases having been very scanty, a definite result could not be obtained.

11. Tables IV-XXV are constructed in the same way as Tables I-II, the "sum" or the "seismic number" being used in the same meaning as the "sum without weight" in the first two tables.

TABLE III.
EARTHQUAKE OBSERVATION AT THE 22
METEOROLOGICAL STATIONS.

Meteorological Station.	Date of commencement of earthquake observations taken into account.	Time interval between Dec. 1902 and the date in the former column.		Date after which observations are excluded for a complete month.	No. of earthquake observations taken into account.
		years.	months.		
Tokyo.	Jan. 1876	27	0	{ Oct. 28, 1891 ; June 15, 1896.	2464
Nemuro.	March 1834	8	9	March 22, 1894.	755
Nagoya.	Jan. 1894	9	0	Jan. 10, 1894.	799
Gifu.	Jan. 1894	9	0	Jan. 10, 1894.	938
Ishinomaki.	Jan. 1886	17	0	-----	1307
Fukushima.	May 1880	13	8	Aug. 9, 1901.	476
Osaka.	July 1882	20	6	Oct. 28, 1891.	293
Mito.	Jan. 1900	3	0	-----	557
Fukuoka.	Aug. 1898	4	5	{ Aug. 12, 1898 ; Feb. 20, 1900 ; April 9, 1900.	410
Oita.	Jan. 1887	16	0	-----	243
Miyako.	March 1883	19	10	-----	923
Aomori.	Jan. 1892	21	0	{ March 22, 1894 ; Oct. 22, 1894 ; April 20, 1896 ; June 15, 1896 ; Aug. 31, 1896 ; Aug. 9, 1900.	631
Hakodate.	Jan. 1873	30	0	-----	366
Akita.	Jan. 1883	20	0	Aug. 31, 1893.	410
Utsunomiya.	Feb. 1891	11	11	-----	677
Maebashi.	Dec. 1876	6	1	-----	270
Yamakata.	Dec. 1889	13	1	Aug. 31, 1896.	235
Niigata.	April 1886	16	9	-----	228
Nagano.	Jan. 1889	14	0	-----	418
Hikone.	Jan. 1874	9	0	Jan. 10, 1894.	289
Wakayama.	Sept. 1879	23	4	-----	472
Kagoshima.	March 1885	17	10	-----	527

Total number of earthquake observations=13678.

TABLE IV.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT TŌKYŌ.
 (Jan. 1876—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	78	3	0	81	0.97
2	68	10	0	78	0.94
3	89	6	0	95	1.13
4	70	7	0	77	0.92
5	69	4	1	74	0.88
6	89	7	0	96	1.14
7	80	6	1	87	1.04
8	76	1	0	77	0.92
9	83	7	2	92	1.10
10	75	2	0	77	0.92
11	82	7	0	89	1.06
12	65	5	1	71	0.85
13	70	5	0	75	0.89
14	63	5	0	68	0.81
15	63	6	0	69	0.82
16	70	11	0	81	0.97
17	84	6	2	92	1.10
18	76	11	3	90	1.07
19	84	7	2	93	1.11
20	75	3	1	79	0.94
21	74	7	2	83	0.99
22	86	8	1	95	1.13
23	88	7	0	95	1.13
24	81	9	0	90	1.07
25	67	1	1	69	0.82
26	73	6	1	80	0.95
27	67	3	1	71	0.85
28	74	11	0	85	1.01
29	93	5	0	98	1.17
30	54	3	0	57	1.30
Sum.	2266	179	19	2464	—

TABLE V.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT NEMURO.
 (March 1894—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	23	5	0	28	1.10
2	25	6	0	31	1.22
3	16	4	0	20	0.79
4	31	2	0	33	1.30
5	17	4	0	21	0.83
6	30	3	0	33	1.30
7	22	5	0	27	1.06
8	21	1	0	22	0.86
9	33	1	0	34	1.36
10	21	4	0	25	0.98
11	27	2	0	29	1.14
12	20	0	1	21	0.83
13	20	2	0	22	0.86
14	20	0	1	21	0.83
15	18	3	0	21	0.83
16	22	2	0	24	0.94
17	15	0	0	15	0.59
18	33	6	0	39	1.53
19	25	4	0	29	1.14
20	22	3	0	25	0.98
21	18	3	0	21	0.83
22	26	3	0	29	1.14
23	17	1	0	18	0.71
24	25	1	0	26	1.02
25	24	6	0	30	1.18
26	18	1	0	19	0.75
27	26	3	0	29	1.14
28	23	2	0	25	0.98
29	21	8	0	29	1.14
30	7	2	0	9	0.67
Sum.	666	87	2	755	—

TABLE VI.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT NAGOYA.
(Jan. 1894—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	17	1	0	18	0.69
2	23	0	0	23	0.88
3	22	1	0	23	0.88
4	28	3	0	31	1.19
5	21	1	0	22	0.84
6	26	1	0	27	1.03
7	16	1	0	17	0.65
8	23	2	0	25	0.96
9	25	2	0	27	1.03
10	19	0	0	19	0.73
11	36	0	0	36	1.38
12	32	1	0	33	1.26
13	20	1	0	21	0.80
14	25	3	0	28	1.07
15	26	4	0	30	1.15
16	27	0	0	27	1.03
17	20	2	0	22	0.84
18	23	1	0	24	0.92
19	23	0	1	24	0.92
20	27	0	0	27	1.03
21	38	1	0	39	1.49
22	18	2	0	20	0.76
23	14	2	0	16	0.61
24	30	3	0	33	1.26
25	29	0	0	29	1.11
26	44	2	0	46	1.76
27	31	2	0	33	1.26
28	21	0	0	21	0.80
29	28	2	0	30	1.15
30	8	0	0	8	0.57
Sum.	740	38	1	779	—

TABLE VII.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT GIFU.
(Jan. 1894—Dec. 1902.)

Synodic day.	Eqke sound.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	1	22	3	0	26	0.82
2	1	23	2	0	26	0.82
3	4	34	2	1	41	1.29
4	0	30	2	1	33	1.04
5	0	36	5	1	42	1.33
6	1	31	2	0	34	1.07
7	1	36	0	0	37	1.17
8	0	24	4	0	28	0.88
9	0	34	2	0	36	1.14
10	1	25	1	0	27	0.85
11	4	28	3	0	35	1.10
12	1	30	3	0	34	1.07
13	4	16	6	0	26	0.82
14	3	36	3	1	43	1.36
15	0	23	2	0	25	0.79
16	1	27	3	0	31	0.98
17	0	23	4	0	27	0.85
18	1	31	1	0	33	1.04
19	3	27	1	0	31	0.98
20	1	31	0	0	32	1.01
21	4	20	3	0	27	0.85
22	0	22	0	0	22	0.69
23	2	25	1	0	28	0.88
24	1	32	4	0	37	1.17
25	3	23	1	0	30	0.95
26	3	30	3	0	36	1.14
27	2	31	1	0	34	1.07
28	1	23	0	0	24	0.76
29	0	35	2	0	37	1.17
30	1	14	1	0	30	0.95
Sum.	44	825	65	4	938	—

TABLE VIII.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT ISHINOMAKI.
 (Jan. 1886—Dec. 1902.)

Synodic day.	Intensity not stated.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	13	30	2	0	45	1.02
2	7	24	2	2	35	0.79
3	9	22	4	1	36	0.82
4	11	31	1	1	44	1.00
5	7	34	4	0	45	1.02
6	11	18	5	0	31	0.77
7	12	35	3	1	51	1.16
8	9	26	6	0	41	0.93
9	10	26	1	0	37	0.84
10	13	41	1	1	56	1.27
11	7	22	8	1	38	0.86
12	10	35	1	0	46	1.04
13	11	31	1	0	43	0.98
14	14	19	3	1	37	0.84
15	23	30	7	0	60	1.36
16	19	34	1	1	55	1.25
17	18	28	5	0	51	1.16
18	8	39	2	2	51	1.16
19	13	27	2	1	43	0.98
20	12	22	1	0	35	0.79
21	12	23	4	1	40	0.91
22	12	24	1	3	40	0.91
23	16	29	2	0	47	1.07
24	15	29	3	0	47	1.07
25	13	42	2	0	57	1.29
26	15	35	5	0	55	1.25
27	12	24	0	2	38	0.86
28	14	25	3	0	42	0.95
29	13	24	4	0	41	0.93
30	5	11	1	0	17	0.73
Sum.	334	840	85	18	1307	—

TABLE IX.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT FUKUSHIMA.
(May. 1889—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	18	0	0	18	1.13
2	14	0	0	14	0.88
3	14	1	0	15	0.94
4	15	1	0	16	1.00
5	10	2	0	12	0.75
6	12	0	0	12	0.75
7	18	0	0	18	1.13
8	16	0	0	16	1.00
9	13	0	0	13	0.81
10	22	0	0	22	1.37
11	11	1	0	12	0.75
12	18	2	0	20	1.25
13	23	0	0	23	1.44
14	21	0	0	21	1.31
15	19	0	0	19	1.19
16	15	0	0	15	0.94
17	16	1	0	17	1.06
18	19	0	0	19	1.19
19	13	0	0	13	0.81
20	10	0	0	10	0.63
21	17	0	1	18	1.13
22	13	1	0	14	0.88
23	17	0	0	17	1.06
24	19	2	0	21	1.31
25	19	0	0	19	1.19
26	17	0	0	17	1.06
27	10	0	0	10	0.63
28	14	0	0	14	0.88
29	16	0	0	16	1.00
30	5	0	0	5	0.56
Sum.	464	11	1	476	—

TABLE X.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT OSAKA.
(July 1882—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	10	2	0	12	1.2
2	12	1	0	13	1.3
3	9	0	0	9	0.9
4	8	1	2	11	1.1
5	3	1	0	4	0.4
6	8	2	0	10	1.0
7	10	0	0	10	1.0
8	8	0	0	8	0.8
9	7	0	0	7	0.7
10	6	0	0	6	0.6
11	9	1	0	10	1.0
12	16	1	0	17	1.7
13	8	0	0	8	0.8
14	7	1	0	8	0.8
15	6	0	0	6	0.6
16	4	0	0	4	0.4
17	9	0	0	9	0.9
18	6	0	0	6	0.6
19	7	1	0	8	0.8
20	14	0	0	14	1.4
21	7	1	0	8	0.8
22	8	2	0	10	1.0
23	6	3	1	10	1.0
24	15	2	0	17	1.7
25	7	0	0	7	0.7
26	15	0	2	17	1.7
27	9	0	0	9	0.9
28	16	1	1	18	1.8
29	8	2	0	10	1.0
30	5	2	0	7	1.3
Sum.	263	24	6	293	—

TABLE XI.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT MITO.
(Jan. 1900—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	22	0	0	22	1.16
2	11	1	0	12	0.63
3	20	1	0	21	1.11
4	16	2	0	18	0.95
5	13	0	1	14	0.74
6	22	0	0	22	1.16
7	14	4	0	18	0.95
8	17	0	0	17	0.90
9	9	0	0	9	0.48
10	15	3	0	18	0.95
11	22	1	2	25	1.32
12	19	0	0	19	1.01
13	26	0	0	26	1.37
14	23	2	1	26	1.37
15	17	4	0	21	1.11
16	16	2	0	18	0.95
17	26	2	0	28	1.48
18	27	2	0	29	1.53
19	11	1	0	12	0.63
20	9	1	0	10	0.53
21	8	2	0	10	0.53
22	20	1	0	21	1.11
23	14	0	0	14	0.74
24	18	4	0	22	1.16
25	11	2	0	15	0.79
26	24	4	1	29	1.53
27	14	0	0	14	0.74
28	15	1	0	16	0.85
29	20	0	1	21	1.11
30	10	0	0	10	1.01
Sum.	511	40	3	557	—

TABLE XII.
SYNODIC-DAILY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT FUKUOKA.
 (Aug. 1898—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	unfelt.	Sum (unfelt excluded).	Reduced.
1	13	0	0	0	13	0.93
2	12	0	0	0	12	1.86
3	14	0	0	0	14	1.00
4	20	0	0	0	20	1.43
5	17	0	0	0	17	1.21
6	10	0	0	0	10	0.71
7	11	0	0	0	11	0.79
8	8	0	0	4	8	0.57
9	11	0	0	0	11	0.79
10	12	0	0	4	12	0.86
11	16	0	0	14	16	1.07
12	13	0	0	2	13	0.93
13	10	1	0	2	11	0.79
14	12	0	0	9	12	0.86
15	15	0	0	4	15	1.07
16	16	0	0	1	16	1.14
17	13	0	0	4	13	0.93
18	22	0	0	11	22	1.57
19	17	0	0	11	17	1.21
20	16	0	0	0	16	1.14
21	12	1	0	0	13	0.93
22	17	0	0	0	17	1.21
23	16	2	2	0	20	1.43
24	16	0	0	0	16	1.14
25	7	0	1	0	8	0.57
26	11	0	0	0	11	0.79
27	16	0	0	0	16	1.14
28	11	0	0	2	11	0.79
29	9	0	0	0	9	0.64
30	10	0	0	0	10	1.36
Sum.	403	4	3	68	410	—

TABLE XIII.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT OITA.
 (Jan. 1887—Dec. 1902.)

Synodic day.	Slight.	Weak.	Strong.	Sum.	Reduced.
1	7	3	1	11	1.34
2	5	1	0	6	1.95
3	8	2	0	10	1.22
4	5	1	1	7	0.85
5	7	0	0	7	0.85
6	4	2	0	6	0.73
7	8	6	0	14	1.71
8	5	2	0	7	0.85
9	6	1	0	7	0.85
10	10	2	0	12	1.46
11	9	3	0	12	1.46
12	3	2	0	5	0.61
13	7	3	0	10	1.22
14	6	0	0	6	0.73
15	5	1	0	6	0.73
16	6	1	0	7	0.85
17	2	3	0	5	0.61
18	8	3	0	11	1.34
19	5	0	0	5	0.61
20	1	0	0	1	0.12
21	7	4	0	11	1.34
22	4	1	0	5	0.61
23	7	2	1	10	1.22
24	5	2	0	7	0.85
25	5	3	1	9	1.10
26	7	0	0	7	0.85
27	4	1	0	5	0.61
28	7	3	0	10	1.22
29	9	2	0	11	1.34
30	3	0	0	3	0.73
Sum.	185	54	4	243	---

TABLE XIV.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT MIYAKO.
 (March 1883—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	28	0.89	11	29	0.92	21	18	0.57
2	27	0.88	12	24	0.76	22	36	1.14
3	34	1.08	13	26	0.83	23	43	1.37
4	29	0.92	14	25	0.80	24	32	1.02
5	29	0.92	15	23	0.73	25	38	1.21
6	33	1.05	16	31	0.99	26	39	1.24
7	47	1.50	17	30	0.95	27	19	0.60
8	49	1.56	18	40	1.27	28	27	0.86
9	27	0.86	19	21	0.67	29	37	1.18
10	44	1.40	20	17	0.54	30	21	1.24

Total seismic number=923.

TABLE XV.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT AOMORI.
 (Jan. 1882—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	20	0.92	11	24	1.10	21	23	1.06
2	23	1.06	12	20	0.92	22	21	0.97
3	18	0.83	13	18	0.83	23	19	0.87
4	21	0.97	14	21	0.97	24	11	0.51
5	23	1.06	15	27	1.24	25	18	0.83
6	28	1.29	16	21	0.97	26	20	0.92
7	22	1.01	17	23	1.04	27	20	0.92
8	27	1.24	18	23	1.04	28	18	0.83
9	20	0.92	19	20	0.92	29	21	0.97
10	15	0.60	20	24	1.10	30	22	1.89

Total seismic number=631.

TABLE XVI.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT HAKODATE.
 (Jan. 1873 – Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	12	0.97	11	16	1.29	21	16	1.29
2	7	0.56	12	9	0.73	22	12	0.97
3	12	0.97	13	16	1.29	23	8	0.65
4	12	0.97	14	13	1.05	24	6	0.48
5	15	1.21	15	7	0.56	25	19	1.53
6	20	1.61	16	16	1.29	26	10	0.81
7	8	0.65	17	12	0.97	27	10	0.81
8	14	1.13	18	10	0.81	28	18	1.45
9	13	1.05	19	10	0.81	29	16	1.29
10	9	0.73	20	13	1.05	30	7	1.05

Total seismic number = 366.

TABLE XVII.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT AKITA.
 (Jan. 1883—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	6	0.43	11	9	0.66	21	12	0.88
2	15	1.10	12	10	0.73	22	16	1.17
3	18	1.32	13	10	0.73	23	21	1.54
4	15	1.10	14	10	0.73	24	18	1.32
5	15	1.10	15	15	1.10	25	13	0.96
6	20	1.47	16	16	1.17	26	16	1.17
7	19	1.40	17	14	1.03	27	13	0.96
8	16	1.17	18	18	1.32	28	6	0.43
9	3	0.22	19	10	0.73	29	18	1.32
10	12	0.88	20	8	0.59	30	8	1.10

Total seismic number = 400.

TABLE XVIII.

SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT UTSUNOMIYA.
(Feb. 1891—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	10	0.43	11	27	1.17	21	19	0.83
2	17	0.74	12	29	1.26	22	18	0.78
3	24	1.04	13	25	1.09	23	30	1.30
4	22	0.96	14	15	0.65	24	32	1.39
5	26	1.13	15	22	0.96	25	23	1.00
6	22	0.96	16	18	0.78	26	33	1.44
7	35	1.52	17	21	0.91	27	23	1.00
8	15	0.65	18	24	1.04	28	24	1.04
9	14	0.61	19	22	0.96	29	31	1.35
10	24	1.04	20	18	0.78	30	14	1.13

Total seismic number=677.

TABLE XIX.

SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT MAEBASHI.
(Dec. 1896—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	7	0.76	11	13	1.41	21	5	0.54
2	8	0.87	12	8	0.87	22	8	0.87
3	8	0.87	13	13	1.41	23	12	1.30
4	9	0.98	14	10	1.09	24	13	1.41
5	6	0.65	15	11	1.20	25	11	1.20
6	10	1.09	16	5	0.54	26	11	1.20
7	12	1.30	17	13	1.41	27	10	1.09
8	4	0.43	18	13	1.41	28	6	0.65
9	5	0.54	19	11	1.20	29	8	0.87
10	4	0.43	20	9	0.98	30	7	1.41

Total seismic number=270.

TABLE XX.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT YAMAGATA.
 (Dec. 1889—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	11	1.39	11	7	0.89	21	10	1.27
2	9	1.14	12	7	0.89	22	6	0.76
3	8	1.01	13	8	1.01	23	13	1.65
4	5	0.63	14	7	0.89	24	7	0.89
5	13	1.65	15	10	1.27	25	8	1.01
6	7	0.89	16	7	0.89	26	11	1.39
7	17	2.15	17	7	0.89	27	6	0.76
8	5	0.63	18	11	1.39	28	5	0.63
9	4	0.51	19	9	1.14	29	8	1.01
10	3	0.38	20	2	0.25	30	4	0.89

Total seismic number=235.

TABLE XXI.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT NIIGATA.
 (April 1886—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	2	0.26	11	10	1.30	21	7	0.91
2	5	0.65	12	6	0.78	22	12	1.56
3	10	1.30	13	8	1.04	23	14	1.82
4	2	0.26	14	4	0.52	24	8	1.04
5	5	0.65	15	7	0.91	25	8	1.04
6	4	0.52	16	4	0.52	26	7	0.91
7	7	0.91	17	14	1.82	27	2	0.26
8	2	0.26	18	21	2.72	28	2	0.26
9	9	1.17	19	11	1.43	29	14	1.82
10	7	0.91	20	12	1.56	30	4	0.91

Total seismic number=228.

TABLE XXII.

**SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT NAGANO.**

(Jan. 1889—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	16	1.10	11	7	0.48	21	13	0.90
2	22	1.52	12	11	0.76	22	15	1.03
3	12	0.83	13	11	0.76	23	9	0.62
4	13	0.90	14	5	0.35	24	16	1.10
5	21	1.45	15	14	0.97	25	17	1.17
6	17	1.17	16	17	1.17	26	16	1.10
7	18	1.24	17	15	1.03	27	16	1.10
8	9	0.62	18	25	1.73	28	11	0.76
9	12	0.83	19	20	1.38	29	14	0.97
10	6	0.41	20	11	0.76	30	9	1.17

Total seismic number=418.

TABLE XXIII.

**SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT HIKONE.**

(Jan. 1894—Dec. 1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	8	0.82	11	12	1.22	21	10	1.02
2	11	1.12	12	12	1.22	22	10	1.02
3	9	0.92	13	7	0.71	23	11	1.12
4	8	0.82	14	15	1.53	24	8	0.82
5	5	0.51	15	12	1.22	25	9	0.92
6	10	1.02	16	7	0.71	26	11	1.12
7	11	1.12	17	9	0.92	27	10	1.02
8	12	1.22	18	11	1.12	28	7	0.71
9	11	1.12	19	10	1.02	29	14	1.43
10	6	0.61	20	7	0.71	30	6	1.12

Total seismic number=289.

TABEE XXIV.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT WAKAYAMA.
 (Sept. 1879—1902.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	15	0.94	11	12	0.75	21	17	1.06
2	13	0.81	12	12	0.75	22	14	0.87
3	19	1.19	13	12	0.75	23	12	0.75
4	21	1.31	14	18	1.12	24	21	1.31
5	16	1.00	15	17	1.06	25	20	1.25
6	16	1.00	16	10	0.62	26	23	1.44
7	15	0.94	17	7	0.44	27	20	1.25
8	14	0.87	18	8	0.50	28	25	1.56
9	17	1.06	19	15	0.94	29	20	1.25
10	18	1.13	20	17	1.06	30	8	0.94

Total seismic number=472.

TABLE XXV.
SYNODIC-MONTHLY DISTRIBUTION OF EARTHQUAKES
OBSERVED AT KAGOSHIMA.
 (March 1885—Dec. 1903.)

Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.	Synodic day.	Seismic number.	Reduced.
1	17	0.96	11	30	1.69	21	15	0.84
2	16	0.90	12	12	0.67	22	9	0.51
3	19	1.07	13	27	1.52	23	11	0.62
4	19	1.07	14	24	1.35	24	16	0.90
5	29	1.63	15	26	1.46	25	16	0.90
6	10	0.56	16	20	1.13	26	11	0.62
7	8	0.45	17	21	1.18	27	23	1.29
8	23	1.29	18	21	1.18	28	10	0.56
9	15	0.84	19	22	1.24	29	22	1.24
10	16	0.90	20	12	0.67	30	7	0.73

Total seismic number=527.

12. Drawing the frequency curves (figs. 3-24) in the way already explained, we notice firstly, that in most cases there occur two distinct pairs of maxima, one about the times of the conjunction and opposition of the sun and moon, and the other at intermediate times; and secondly, that the first pairs of maxima is pronounced at certain stations, and the second pair at some other stations, while at the remaining stations the two pairs develop equally well. The relation expressed in the second statement may possibly be due to the fact that the observed earthquakes were mostly of inland origin, or of submarine, or of both origins. With this view, I have grouped the different stations into three sets (*A*), (*B*), and (*C*), according as their observations related mostly to inland earthquakes, both inland and submarine, and submarine respectively. Table XXVI shows this arrangement and grouping; the frequency curves at the different stations have also been arranged in the same order. The numbers in the right hand columns of the table are the days at which the frequency curve reaches their maximum height, days relating to more pronounced being printed with fat letters.

TABLE XXVI.

Group.	Meteorological stations.	Day of Maximum Seismic Number.			
A	Nagoya.	2	18	6	26
	Fuknoka.	30	18	4	23
	Niigata.	30	18	11	23
	Tokyo.	30	18	7	23
	Kagoshima.	29	14	4	—
B	Gifu.	29	14	—	25
	Osaka.	28	12	—	—
	Nagoya.	4	15	11	21,25
	Wakayama.	28	14	4	20
	Aomori.	30	15	7	20
	Oita.	2	18	9	24
	Hikone.	29	14	8	—
C	Maebashi.	30	15	7	24
	Mito.	30	14	6	26
	Hakodate.	28	—	6	21
	Nemuro.	—	18	9	26
	Yamagata.	1	15	7	23
	Fukushima.	2	13	7	24
	Ishinomaki.	1	16	10	25
	Utsunomiya.	29	12	6	24
	Akita.	30	17	6	23
	Miyako.	30	17	8	24
	Average.	30	15	7	23

13. Let us now compare the frequency curves in the two extreme cases, namely, those of Nagano and Miyako. The former station which is situated in the high land of Shinano, about 180 km. distant from the Pacific coast is disturbed mostly by local shocks, earthquakes which occurred in the Pacific basin having been registered there only when the disturbance was very strong at the origin. In the frequency curve, we notice one distinct pair of maxima on the 2nd and 18th. The seismic number in each of these days is about 3 times of the

minimum and 1.6 times of the daily average. Another pair of maxima occurred on the 6th and 26th.

14. Miyako is, on the other hand, situated on the Pacific coast bordering the earthquake region which runs parallel to the coast line at a distance of some 100 to 200 km. from it. Earthquakes which were felt at Miyako originated mostly in this zone, with a few exceptions of shocks which occurred in the eastern part of Mutsu province. The frequency curve has a pair of the pronounced maxima on the 8th and 24th, the seismic number in each of these days amounting to 2 times or more of the minimum and 1.5 times of the daily average. A pair of minor maxima occurred on the 30th and 17th.

15. Thus we see that the days of maximum seismic number for the two stations coincide almost with each other, the only difference being that the days of pronounced pair in one station is replaced by those of minor pair in the other. The state of things is very similar between the frequency curves to the stations (*A*) and (*C*), though the difference is not so distinctly marked as in the two typical stations. It will also be seen that the stations in the group (*B*) stand between the two other groups so far as the above-mentioned characteristic is concerned.

16. For the sake of comparison, I give another example of the distribution of submarine earthquakes. Among the earthquakes contained in the Earthquake Inv. Comm. Catalogue there are 28 large ones which were accompanied by destructive sea-waves, and 62 others which were not apparently accompanied by sea-waves but which may be inferred, on account of the disturbed area, to have originated at sea coast places or under the sea. These two sorts of earthquakes are tabulated as follows:—

TABLE XXVII.

Synodic day.	Number of earthquakes.			Synodic day.	Number of earthquakes.		
	With sea-waves.	Without sea-waves.	Sum.		With sea-waves.	Without sea-waves.	Sum.
1	0	2	2	16	2	3	5
2	0	2	2	17	0	0	0
3	0	0	0	18	0	2	2
4	2	1	3	19	1	3	4
5	1	6	7	20	0	2	2
6	0	2	2	21	1	3	4
7	1	6	7	22	2	3	5
8	1	0	1	23	2	6	8
9	0	4	4	24	1	3	4
10	0	1	1	25	3	3	6
11	0	1	1	26	3	3	6
12	1	1	2	27	1	0	1
13	0	0	0	28	1	3	4
14	2	2	4	29	0	1	1
15	1	1	2	30	1	0	1
				Sum.	28	62	90

From this table, it will be seen that the greatest number of the submarine earthquakes occurred about the 23rd, and the next greatest about the 7th and the 16th, the state of things being very similar to the fact remarked in connection with the observations at the different Meteorological Stations.

IV. Causes of the four maxima in the frequency curves.

17. The existence of two maximum seismic numbers at the times of the conjunction and opposition of the sun and moon, being due to the joint effect of these two heavenly bodies, does not require further discussion. The following may be an explanation for the existence of the other pair at the 7th and 23rd.

18. According to Dr. Omori, the barometric pressure has marked influence upon the seismic frequency in Japan; the curves showing the time variations of the two quantities being similar to each other. Now the barometric pressure which reaches in its diurnal variation

its maximum at 9h and 22h, will interfere with the tidal force helping or cancelling the latter according as high-water or low-water occurs at these times. In Tokyo, the synodic days corresponding to the former case are the 7th and 22nd, the days corresponding to the latter are the 12th and 27th. Allowing an hour or two for time difference of occurrences of maximum tidal and barometric pressures at other localities, the days 6th-9th and 21st-24th are ones in which the resultant of the two influences becomes most effective. Thus we may look for the maximum seismic numbers about the 7th and 22nd which correspond roughly to the actual maxima in question.¹

Although the diurnal variation of seismic frequency follows generally that of barometric pressure, yet we see in several cases that the former variation does not necessarily follow the latter. Thus in the curves of diurnal variation of seismic frequency for Nemuro and Nagoya we notice several maxima in the following hours, those in the first column relating to the more pronounced maxima.

Nemuro . . . 4.0-11.5 (a.m.) . . . 5.0-7.0 (p.m.).

Nagoya . . . 1.5 (a.m.), 4.5 (a.m.) . . . 10.0 (p.m.).

If there are causes which influence the seismic occurrences of these regions at such hours, they will interfere with the tidal force and will give rise to a great number of seismic occurrences at the days when high-water and the assumed causes take place at the same time. These days are found in cases of Nemuro and Nagoya as follows:—

Nemuro . . . 1-10, 16-25. . . 3-6, 17-20.

Nagoya . . . 10, 25; 13, 28. . . 7, 21.

On comparing these days with the days of actual maximum seismic number, we see at once that a tolerably fair correspondence exists between the two as it is indicated in figs. 18 and 10, in which the days found from deduction are given in larger letters along the axis of x .

1. This explanation was suggested to me by Dr. Honda of the Physical Institute of the Sc. Coll., Imp. Univ. Tokyo.

20. With the above-stated view, I have constructed the following table in which the days of actual and deduced maximum seismic numbers are so arranged as to be readily comparable. From the table, it will be seen how tolerably well the days found by the two different methods agree with each other.

Station.	Time of high-water, relative to that of Tokyo Bay.	Hour of occurrence of maximum in diurnal seismic variation. Synodic days in which hours in the above column and of high-water coincide. Synodic days of actual maximum seismic number.	Hour of occurrence of maximum in diurnal seismic variation. Synodic days in which hours in the above column and of high-water coincide. Synodic days of actual maximum seismic number.	Hour of occurrence of maximum in diurnal seismic variation. Synodic days in which hours in the above column and of high-water coincide. Synodic days of actual maximum seismic number.
Tokyo.	0	9.5 ^h am.	7,22 6,22	
Kagoshima.	+1.0	1.5 am,pm.	10,26 11,27	6.5(slight) 1,16 ?
Gifu.	+0.6	4.5 am.	13,28 14,29	0.5(slight) 10,24 9,24
Nagoya.	+0.6	1.5(large) am.	10,25 11,26	4.0 14,28 15,29
Wakayama.	0	4.5(slight) am.	14,29 14,28	7.0(slight) 4,18 4,20
Aomori.	-1.0(?)	1.5 am.	11,27 11,26	9.5 7,24 8,26
Nemuro.	-1.6	4.0 am.	1,16 2,18	11.5 10,25 9,25
Fukushima.	-1.0	9.5 am.	7,24 7,24	7.0 4,21 4,21
Ishinomaki.	-1.3	2.5 p.m.	13,28 15,25	
Utsunomiya.	-0.5(?)	9.0 am.	6,23 7,26	7.5 4,21 5,23
Miyako.	-1.0	1.5(slight) am.	12,26 (?) 26	9.5 8,23 8,23

V. Conclusion.

21. Earthquake occurrences in Japan, when they are distributed

in synodic days, reach the greatest number at two pairs of times, namely :—

Firstly, at the times of the conjunction and opposition of the sun and moon, the combined effort of the two heavenly bodies being the cause ;

Secondly, at the times of quadrature, the combined effort of the moon and barometric pressure being the cause.

22. I have confined myself to the study of the historical earthquakes in Japan, and the recent earthquakes registered by ordinary Gray-Milne type seismographs at the 22 Meteorological Stations in Japan. In the next occasion, I wish to study the synodic monthly distribution of the earthquakes which originated only in the immediate vicinity of Tokyo, and further the relation of the occurrence of each earthquake with the tidal and barometric pressures of successive days.

Nov. 9th, 1903.

Seismological Institute.

Explanation of Figures.

Figs. 1-2 show the synodic monthly distribution of historical earthquakes.

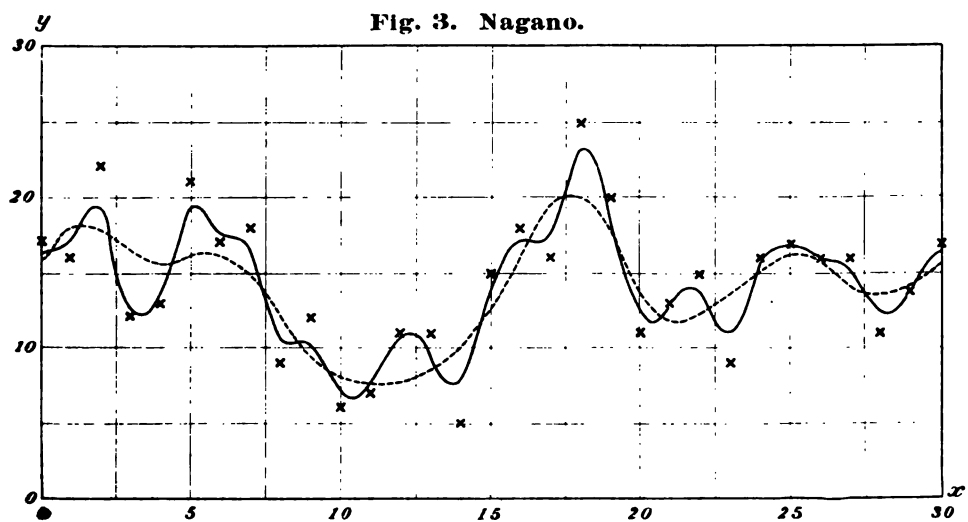
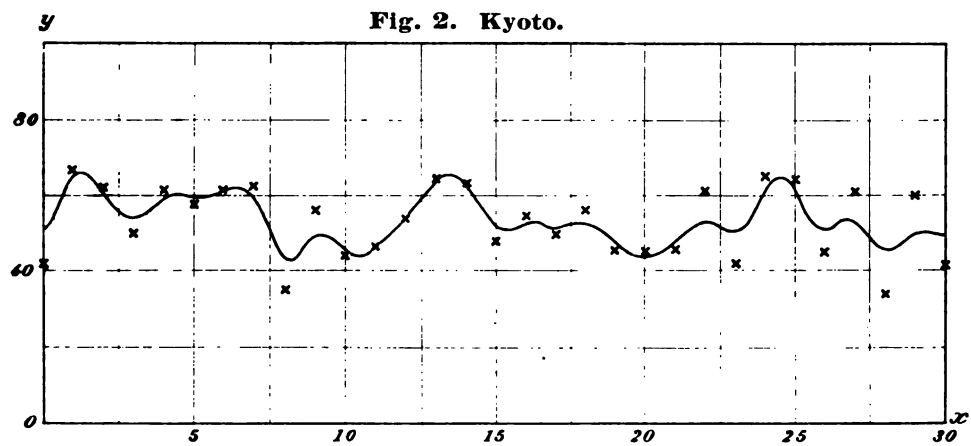
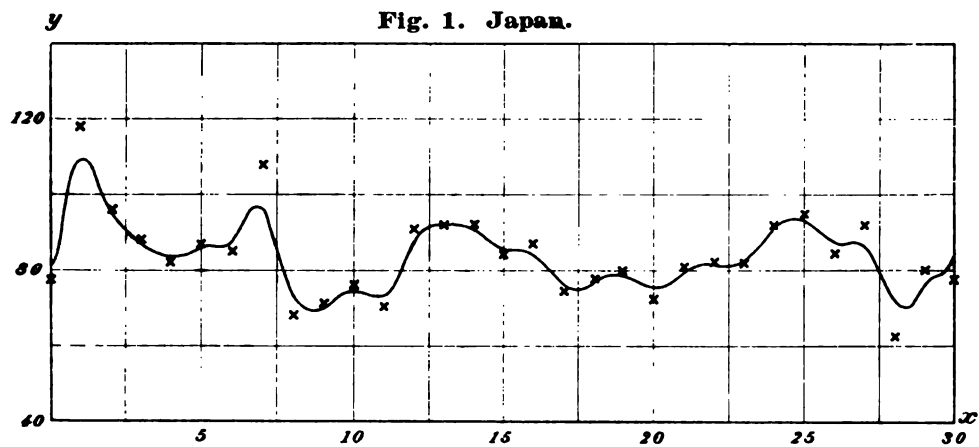
Figs. 3-24 show the synodic monthly distribution of the instrumental observations of recent earthquakes.

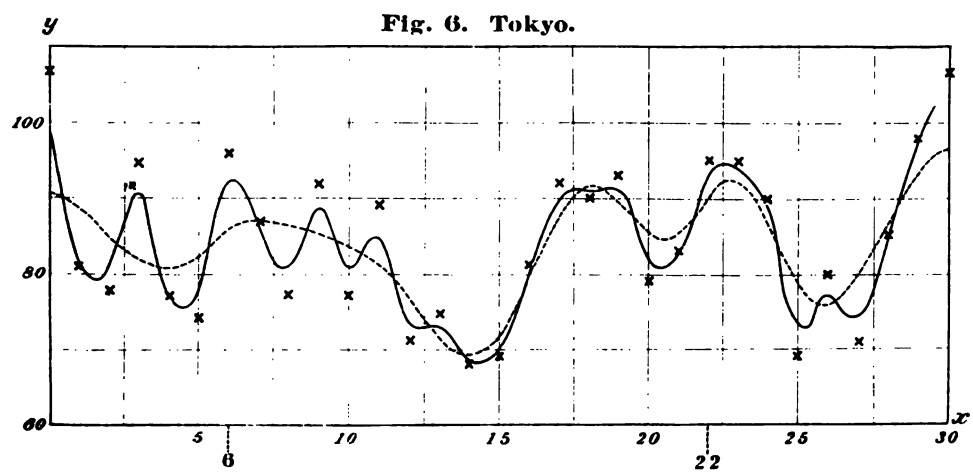
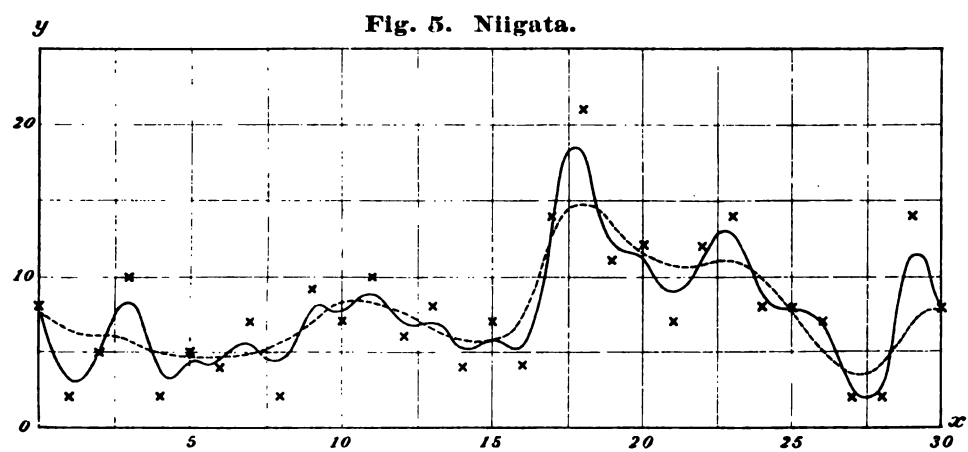
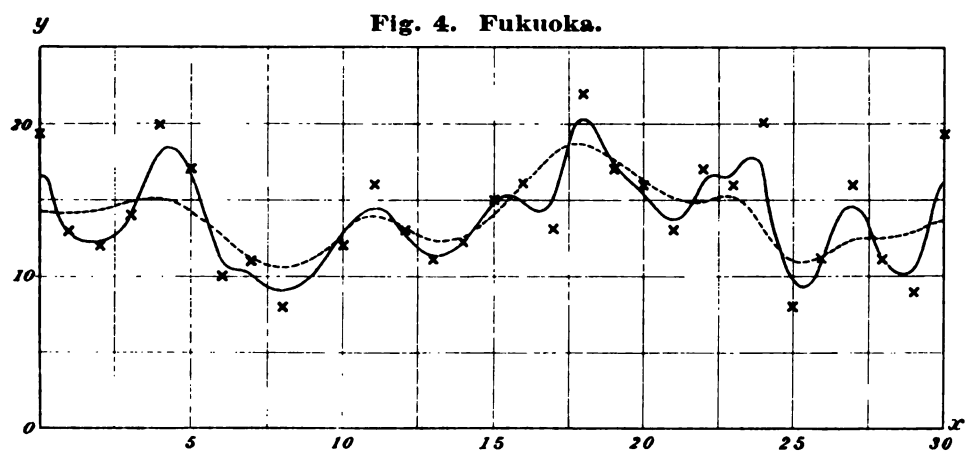
For figs. 1-24:

x =Japanese synodic day.

y =actual number of seismic observations at the corresponding day.

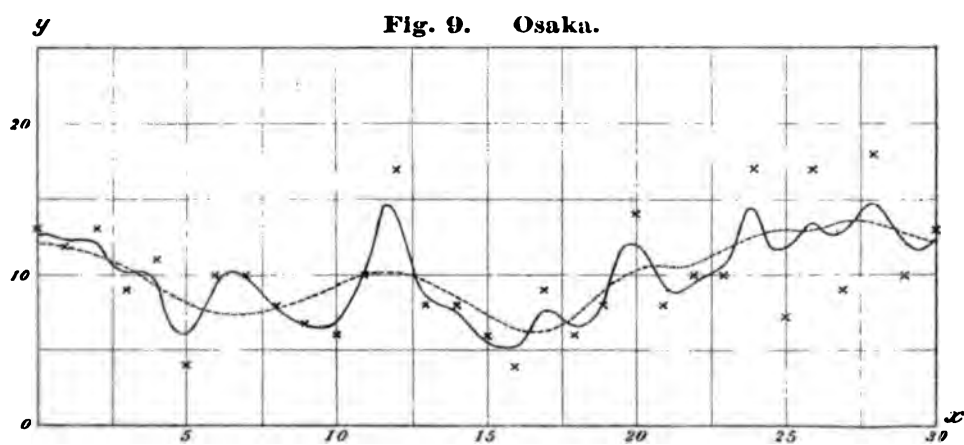
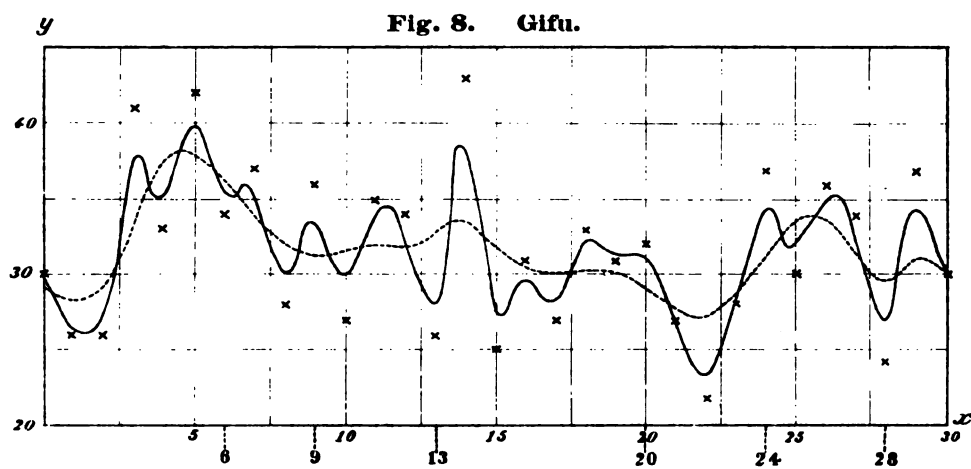
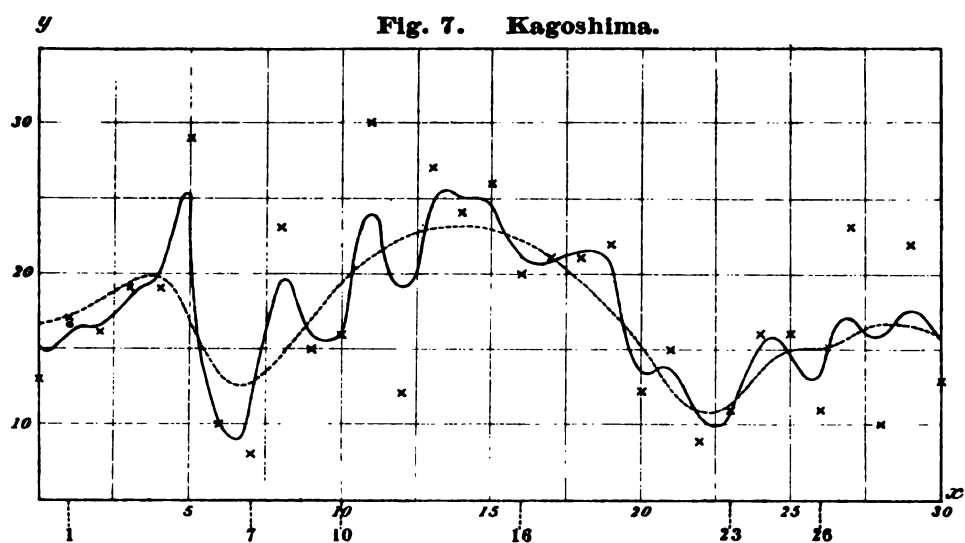
Number in larger letters along the axis of x in figs. 6, 7, 8, &c. indicates the day of *deduced* maximum seismic number (Chapter IV).





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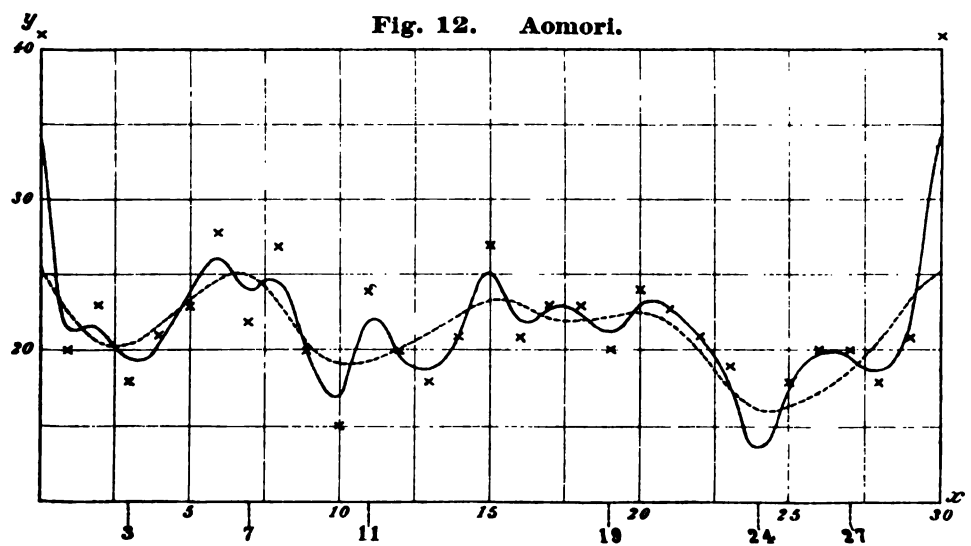
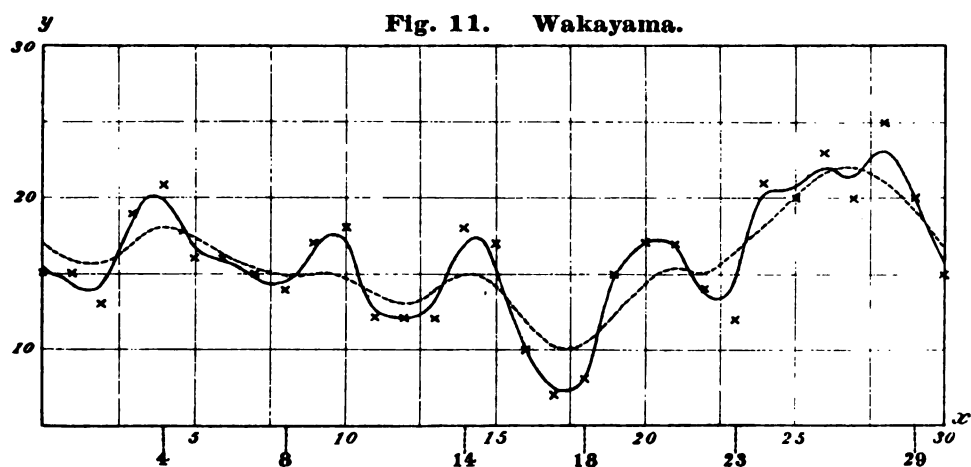
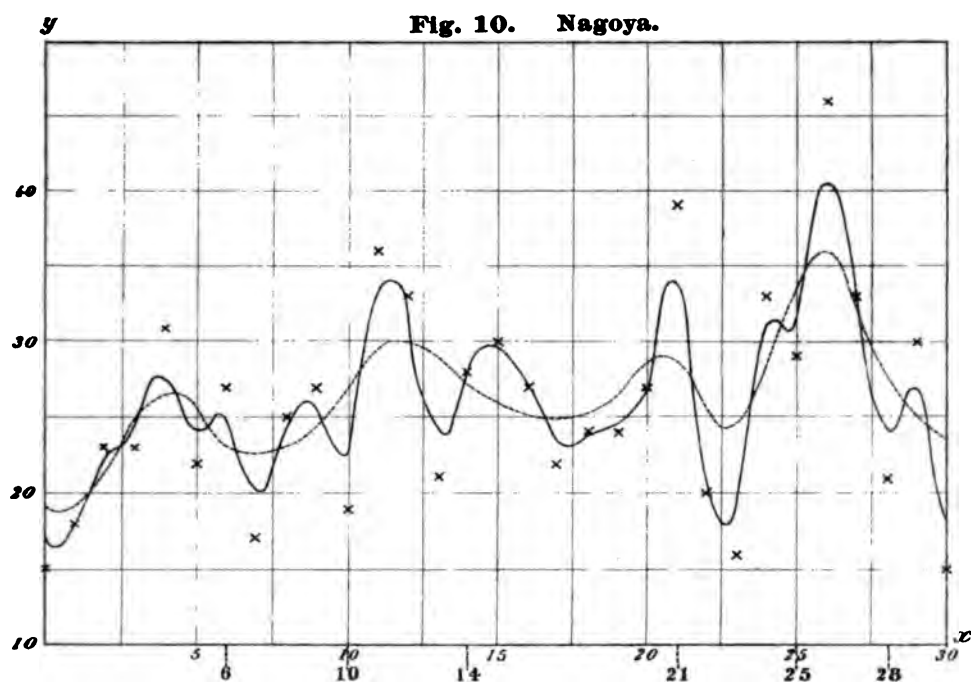


Fig. 13. Oita.

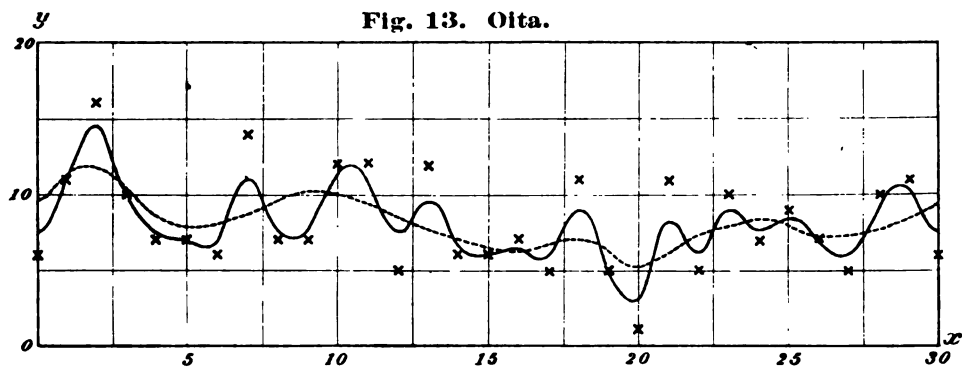


Fig. 14. Hikone.

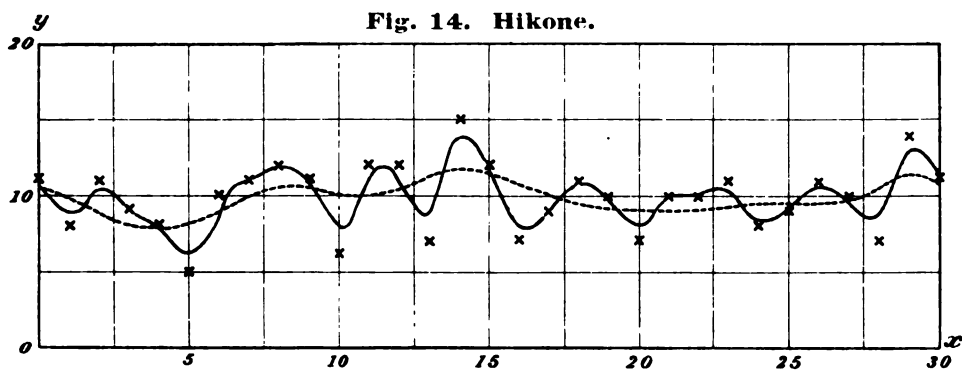
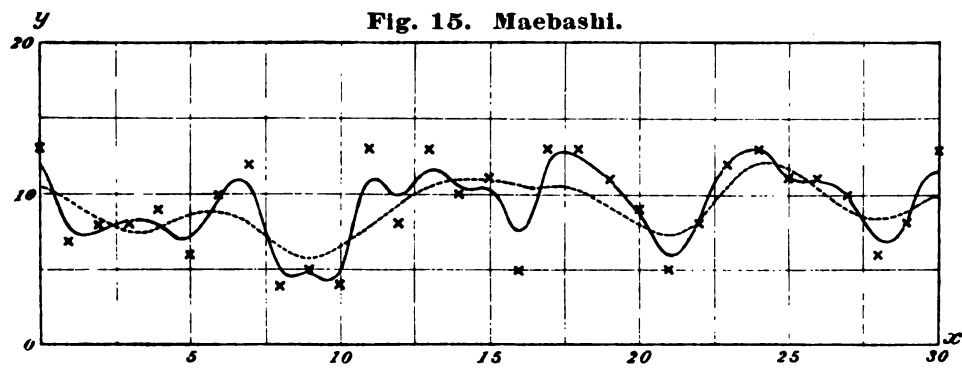


Fig. 15. Maebashi.



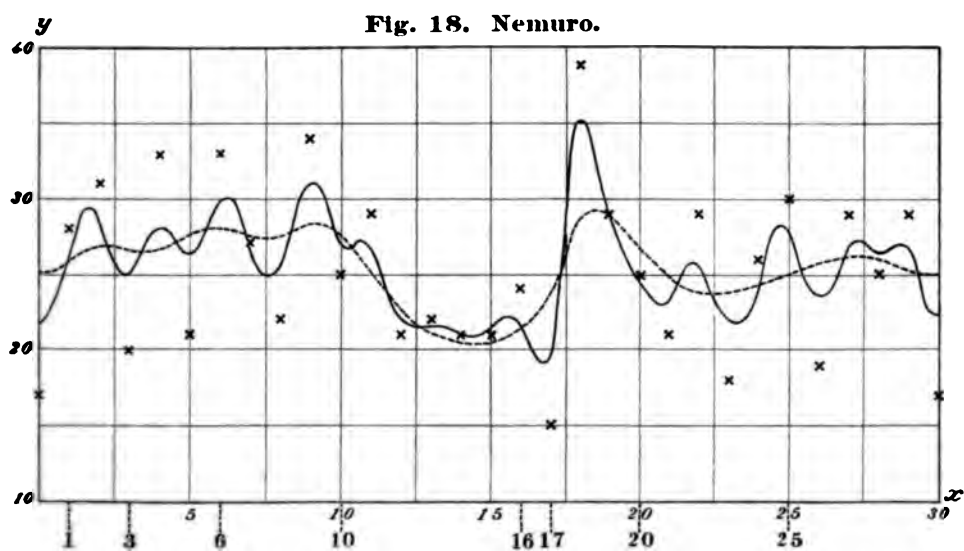
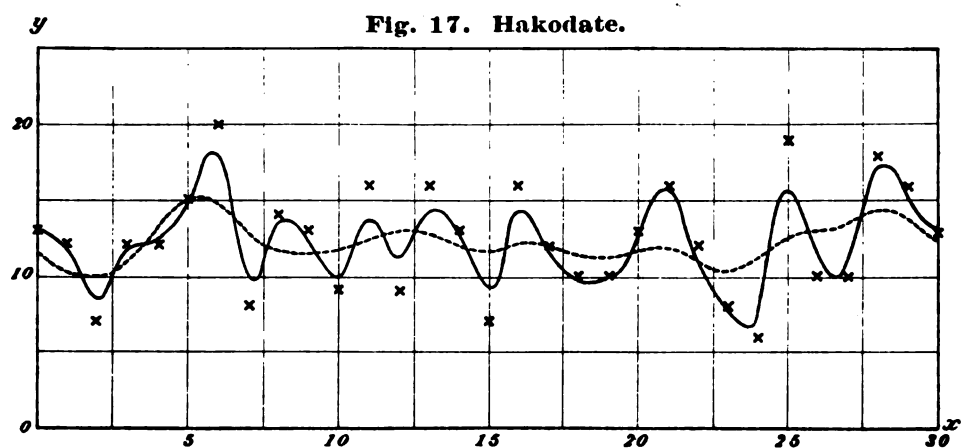
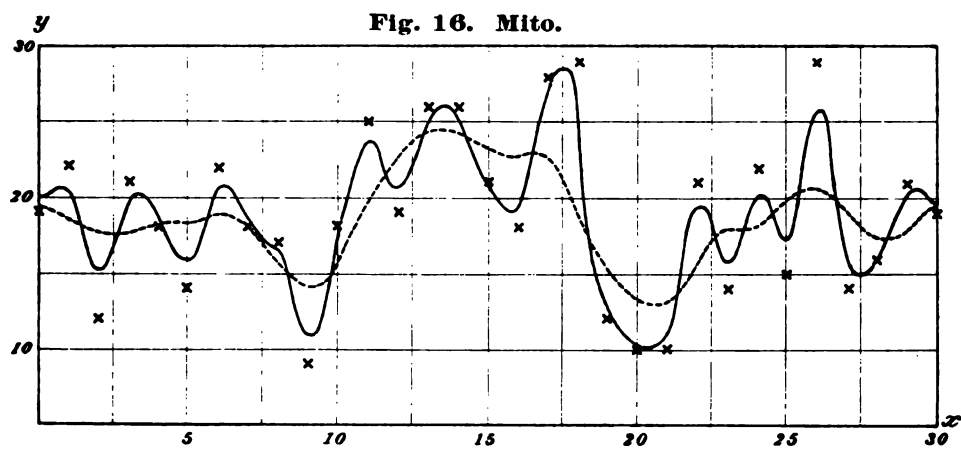


Fig. 19. Yamagata.

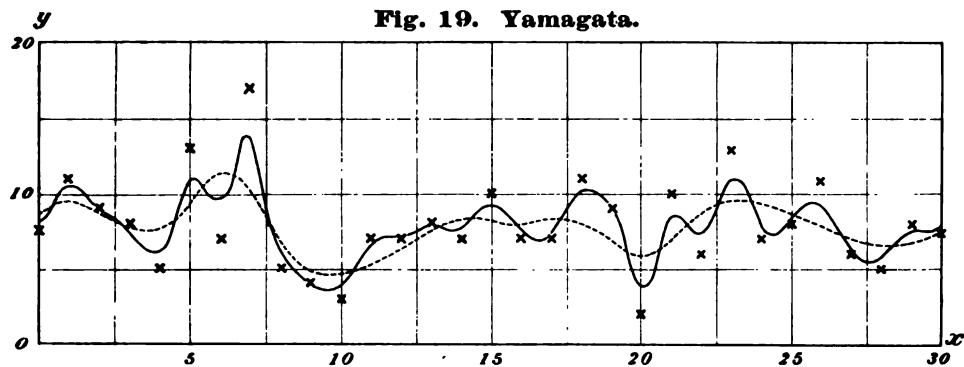


Fig. 20. Fukushima.

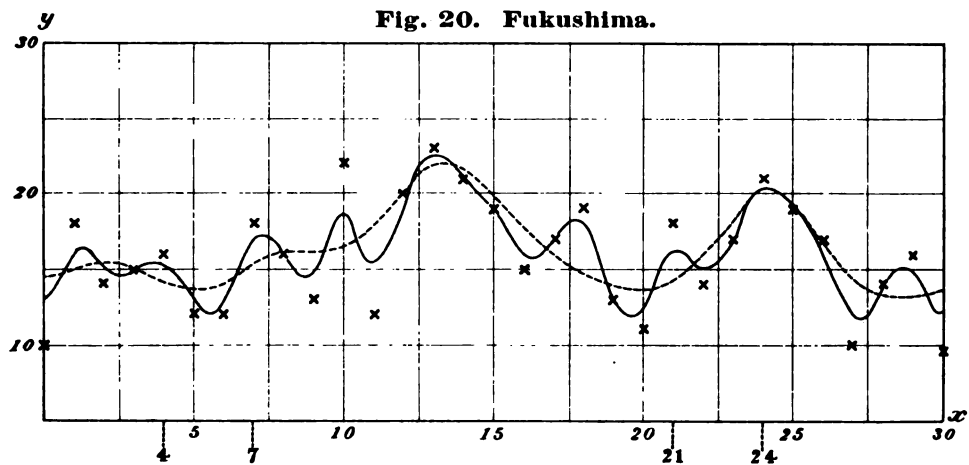


Fig. 21. Ishinomaki.

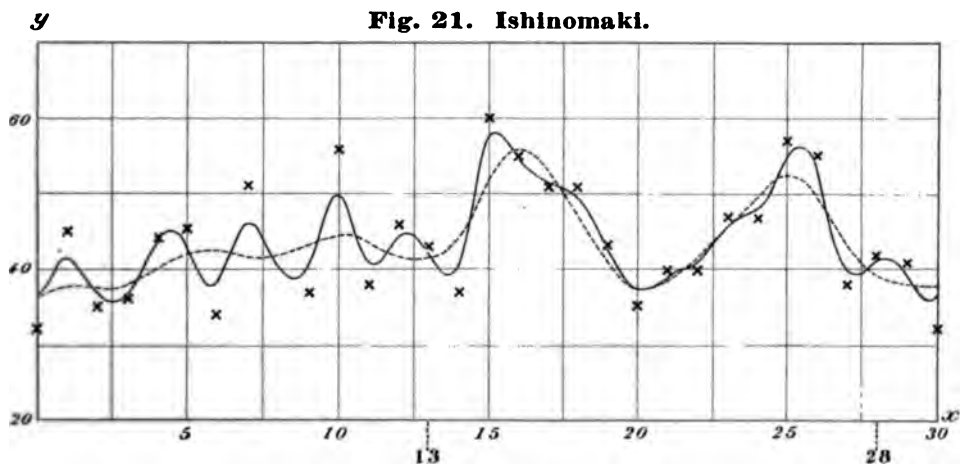


Fig. 22. Utsunomiya.

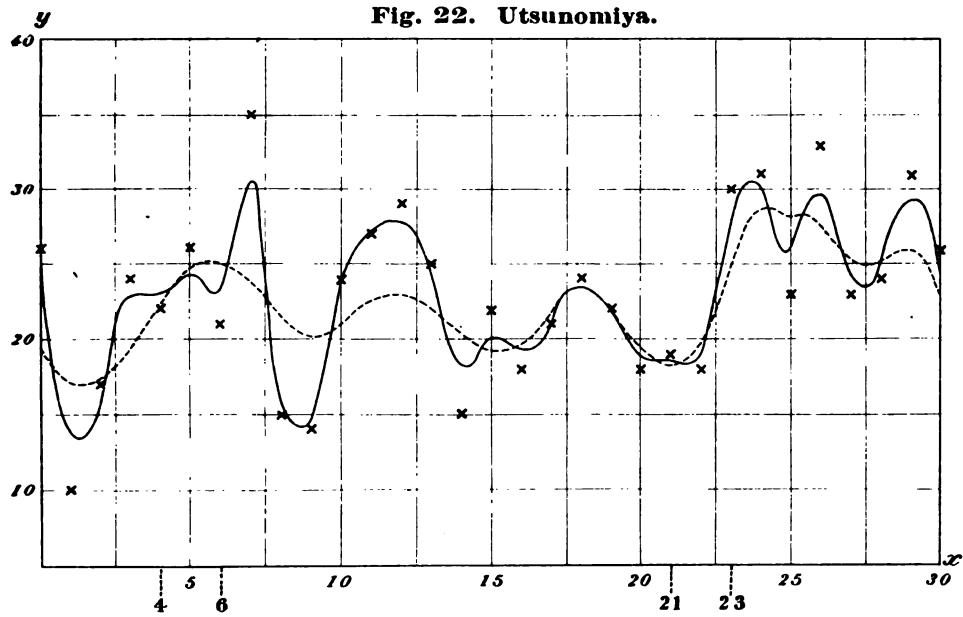


Fig. 23. Akita.

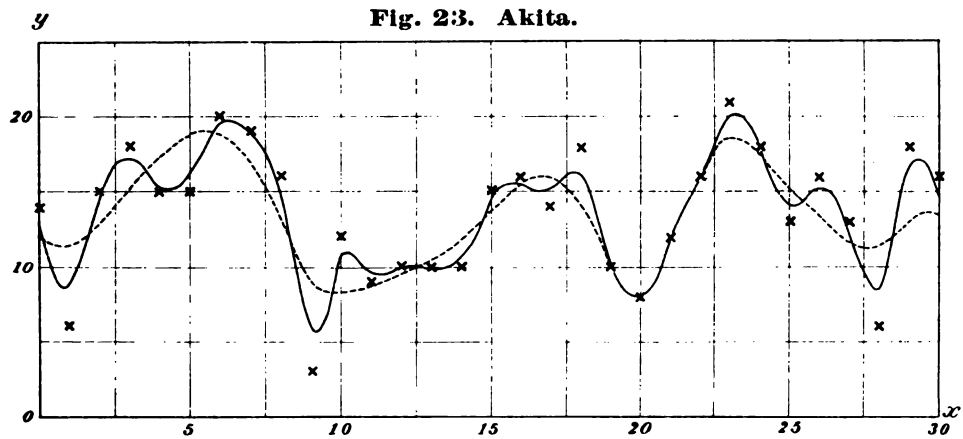
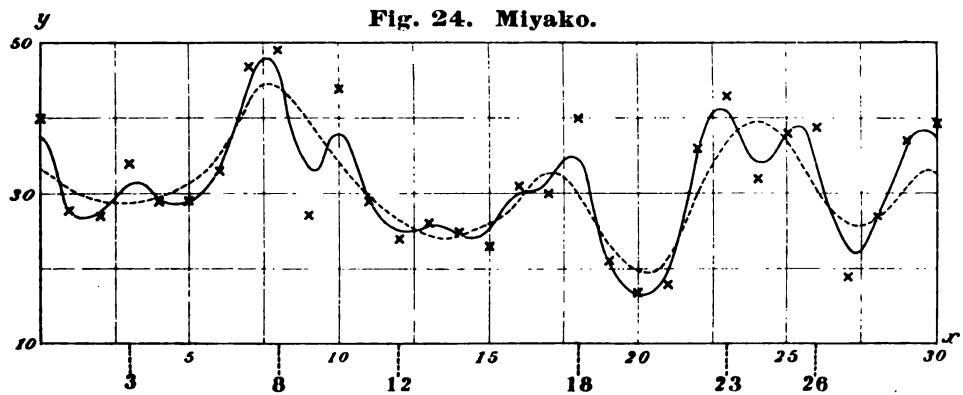


Fig. 24. Miyako.



Daily Periodic Change of the Level in Artesian Wells.

By

K. Honda, *Rigakuhakushi.*

With Plates XVIII–XXIII.

It is well known that in some natural springs, the rate of flow of water is quite parallel with the change of barometric pressure. The parallel change between the pressure and the level of the water was also observed in common wells,* which were not in use. Assistant Professor S. Nakamura observed the periodic change of the level in an artesian well in the compound of the Tōkyō Imperial University, and pointed out that its change is parallel to that of the barometric pressure, with its phase reversed. Being unable to continue this investigation, he left to me the further study of the phenomena. I also carried out similar investigations in artesian wells in Yokohama, Yoshiwara and Ōkubo. In three of these wells, the effect of the tidal motion on the level of water was observed in a remarkable manner. The following pages contain the results of observation in these wells.

Artesian Well in Tōkyō.

The well is at a place 15 m higher than the level of the sea, and 5.7 km distant from the nearest sea coast. It is 380 m deep, and its water-head is 3.2 m below the surface of the ground. The wall of the

* Wilhelm Krebs, *Meteorol. Zeitschrift* VIII, p. 235, 1891. Franz Weyde, ditto, XX, p. 364, 1903.

well consists of stout iron tubes 14 cm in diameter jointed together one after another; the bottom of the well is closed by a long wooden plug, but the water may flow in or out through the interspace between the plug and the iron tube.

My arrangement which was a modification of Mr. S. Nakamura's, consisted of a buoy made of sheet zinc and a wire which was attached to the buoy and stretched vertically upwards by means of a pulley and

Fig 1.



Fig. 2.



a counter weight (Fig. 1.) The buoy carried a lead weight in its lower end, and the pulley rested in two agate caps by its horizontal axis. The motion of a point on the wire was recorded on a cylinder, rotating about a vertical axis, by a pen attached to the wire. To get the steadiness of the pen, and at the same time to diminish the friction as much as possible, the pen-holder carried two arms perpendicular

to the pen. At each end of these arms, a friction-wheel was fixed; the wheels rolled in the V-shaped grooves in two vertical guides.

The recording cylinder had the diameter of about 9 cm and revolved once per week. In some cases, the barometric pressure was also recorded on the same cylinder with the aneroid of six plates.

The present apparatus, when it is arranged as shown in Fig. 2, is very simple and portable, and may with advantages be used in the observation of the seiches.

The record was continuously taken from 4th of March to 17th of September in the last year, and also from 15th of October up to the present. Some of the records are given in Figs. 1, 2, 3. An examination of these records leads us to the following conclusions:—

1. In general the level of the water changes very regularly in passing through two maxima and minima in every 24 hours. The double amplitude varies from 3 cm to 1.

2. In days near the conjunction and the opposition, the succession of the daily maxima and minima is very regular, resembling the form of the ocean-tide. In these days, the amplitude is markedly greater than that in the quadratures.

3. The phases of the maxima and minima coincide with those of the tide in Tōkyō Bay, the high water corresponding to the high level.

4. In days near the conjunction and the opposition, the maxima and minima of the daily barometric change nearly occur at the opposite phases with that of the level; but as we recede from these days, the relative displacement of the phases proceeds in one direction. In days near the quadrature, the maxima and minima of the level change frequently occur just in the same phase as those of the barometric change.

5. The high barometer causes the lowering of the level, and the low one the rising of the level.

6. The rain or dry weather does not sensibly affect the level of the well.

As the probable causes of the change of level, we may mention

- (a) the change of atmospheric pressure,
- (b) the ocean-tide,
- (c) the combined effect of these two.

The lower end of the well may probably be connected to a porous layer, filled with water and extended to a large area. The gas dissolved in water may accumulate in the upper parts of the layer and remain there compressed. Though the gas is scanty in each part, its whole volume may amount to a very large one, when integrated over the whole area; they act therefore as a large air cavity. When the atmospheric pressure increases, the water flows into this space and compresses the enclosed gases; when the pressure decreases, the water flows back into the well by the pressure of the compressed gases. The tide also causes the change of the underground pressure; this change of pressure, if it acted on the porous layer, causes the level of the well to be raised or lowered. The high water then corresponds to the rising, and the low to the falling of the level. Since the water-head of the well is about 12 m higher than that of the sea, it is not probable that the free communication exists between the well and the sea.

Comparing the curves in the barograph with those of the level change, it may safely be concluded that the high or low barometer extending for one or several days results in the change of level with amplitude magnified about 4.35 times.

As regards the causes of the daily change of the level, the daily barometric change and the ocean-tide may act simultaneously, but judging from the forms of the curves, these two causes can not enter with equal importance, because their forms are too simple to be the effect of such a combination. If the first cause predominates, the positions of the maxima and minima can not regularly be displaced in one direction, as actually observed. The tidal effect must therefore be considered as the principal term in the daily change of level.

To assure the above inference, an arrangement artificially changing the pressure in the well was provided. A square brass plate with a hole in its middle part was horizontally soldered to the iron tube. A large bell jar was tightly fixed on the plate with the recording apparatus within it. The air inside the jar could be exhausted or compressed, the pressure of which was measured by the water or mercury manometer. With this arrangement, I studied the relation between the change of pressure and that of the level. The result is given in the following table:—

Pressure difference (p) in mercury.	Level change (h) in the well.	Ratio h/p (abs. value.)
−0.66 mm	+7.5 mm	11.4 mm
−1.61	+20.5	12.7
−4.53	+58.7	13.0
+1.49	−19.3	13.0
+4.02	−52.7	13.1
−9.56	+129.2	13.5
−241.8	+3267.	13.5

The above table shows that the level change for the pressure difference of 1 mm of mercury becomes greater as the change of pressure increases, soon approaching to an asymptotic value 13.5. The last pressure in the table is the pressure which was necessary to raise the level of the water to the mouth of the iron tube. The increase of the ratio h/p with the pressure may be explained to be the effect of the plug at the bottom of the well, because it prevents free motion of the water. The above result indicates the existence of the space filled with evolved gases, as I have already remarked.

When the pressure was applied or reduced, the level descended or ascended according to the logarithmic law with respect to time, as shown in Fig. 4. The form of the curve for the application of pres-

sure or of exhaustion is always steeper than that for the release. It is to be remarked that though a given pressure was first applied, the level change caused the change of the volume in the enclosed air, and therefore the pressure was continuously changing as the time proceeds, till its final value was reached.

It appears from the above experiment that the daily change of the level is of such an amplitude as to be wholly explained by the daily barometric change. But it must be noticed that if the atmospheric pressure changes, it is partly transmitted through the earth crust and therefore the underground pressure must be affected. This change of the underground pressure produces the opposite effect on the level as the pressure acting on the head of the water. Thus the natural pressure produces the differential effect, so that the change of level for the pressure difference of 1 mm of mercury is only 4.35 mm, as actually observed. Hence the level change by the atmospheric pressure amounts only to 32 % of the change by the artificial pressure ; the earth crust transmits therefore about 68 % of the pressure on its surface to a depth of 380 m. By the above consideration, it is now clear that the daily change of pressure generally causes the change of level ranging from 7 mm to 2. Since the amplitude of the daily level change is from 3 cm to 1, the barometric change must be considered as of second importance in the daily change of the level. The principal cause is then the tidal motion ; as we have noticed, the phase of the level change is the same as that of the tide in Tōkyō Bay, and therefore the phenomenon must be considered as due to the tidal pressure. All the particulars above enumerated are well explained by this consideration.

As we have already remarked, the high pressure causes the falling of the level and the low the rising of it. If, however, the jar be sealed air-tight and also thermally, the effect of high and low pressures would reverse the phase of the level-change, because in this case, the pressure above the level does not change, while it acts on the neighbouring earth crust. To test this point, the jar was completely sealed

and thickly covered with blankets and saw dust; the effect of the change of temperature was thus avoided. In this case, we also observed two maxima and minima in every 24 hours with the phases coinciding with those of the tide. The high and low barometers caused the rising and the falling of the level respectively, as it was expected. Fig. 5 is an example. In all cases, the amount of the level change was considerably reduced.

The reduction of the level change can be calculated in the following way. Let S be the area of the cross section of the iron tube, l its whole length, and h the height of the water level from the bottom of the well. Let p and P be the pressure of the sealed air and the underground pressure at the bottom of the well respectively, both expressed by water column. Then we get two equations

$$p + h = P \text{ and } pS(l - h) = \text{const.}$$

$$\therefore \frac{dh}{dP} = \frac{l - h}{p + l - h} = \frac{1}{1 + \frac{p}{l - h}}.$$

In the present experiment,

$$p = 76 \times 13.6 = 1030, \text{ and } l - h \text{ is equivalent to } 539 \text{ cm;}$$

$$\text{therefore} \quad \frac{dh}{dP} = 0.343,$$

which gives the rate of the level change due to unit change of underground pressure. As an example, we take a high barometer on 23rd—24th of September, 1903; the pressure difference in the noons of these days was 9.98 mm. The corresponding change of underground pressure at the bottom of the well is therefore 6.78 mm and its equivalent water column is 9.25 cm, so that

$$dP = 9.25 \text{ and } dh = 0.343 \times 9.25 = 3.17 \text{ cm.}$$

The actually observed value is 3.1 cm, which fairly agrees with the above calculation.

Near the artesian well, there is a common well 10 m deep; its level change was observed with a similar arrangement. Neither the

pressure nor the tide affected, in a least degree, the level of the well ; but the level was greatly influenced by the rain.

In passing it may be observed that in our records we sometimes observed a very regular harmonic curve (Fig. 6), in several successions, which if not so distinct, appeared also in the barograph ; the period of oscillations was about 29 minutes. Thus, it is evident that in the atmosphere, such an oscillation is sometimes produced.

Artesian well in Yokohama.

The well at Negishi in Yokohama is about 2 m higher than the sea level and 2 km distant from the sea coast. It is 300 m deep ; its upper 30 m is protected with iron tubes 15.3 cm in diameter. The well belongs to Mr. Numashima, to whom my best thanks are due. The water in the well was constantly flowing out over the tube ; it was therefore necessary, for my experiment, to raise the head of the water to a suitable height so as to stop the flow of water. An iron tube 5 cm in diameter and 8 m long was vertically erected and tightly jointed to the thick tube by means of a joint-piece. The water soon rose to a height of about 3 m from the earth surface ; it was therefore difficult to arrange my apparatus at such a high place. But the preliminary experiment showed that the daily level change was more than 12 cm ; the following arrangement was therefore adopted.

Near the earth surface, a small side tube was branched ; through a cork plug, it entered into a large bottle containing a quantity of mercury. From the bottom of the bottle, a glass tube 5 mm thick was erected through the cork ; the upper part of the tube was about 4 times thicker. The mercury in the bottle then arose in this tube by the pressure of the water column. The level change in the main tube appeared then as the motion of the mercury-meniscus in the glass tube, its amplitude being reduced to $1/14.1$. To record the motion of the meniscus on a cylinder, a hollow ebonite disk with a vertical wooden rod was floated on the mercury. The upper end of the rod

carried a pen of a similar construction as that used in the Tōkyō artesian well, and the motion of the pen was also guided by two vertical rods.

The record was taken from 18th of last November to 7th of February in this year. Figs. 7 and 8 are two examples. The following is the result of observations:—

(1) The mean level of the water during the day constantly increased from the first day when the tube was erected, up to the the 97th. The mean levels in several days are given in the following table:—

Nov. 14, 2 ^h P. M., 1903	3.10 M
15, noon	3.90
16, „	4.25
18, „	4.65
22, „	5.28
30, „	5.64
Dec. 10, „	6.11
20, „	6.42
30, „	6.70
Jan. 10, „ 1904	6.87
20, „	7.00

Thus the rate of increase of the level becomes gradually less; but it does not vanish up to February 20th. The mean level increased more than double its initial value during about 60 days.

(2) The daily level change has an amplitude of about 10–14 cm, the phase of the change coinciding with that of the tidal motion in Tōkyō Bay.

(3) The atmospheric pressure has the similar effect on the level change as in the Tōkyō well. The level change for the pressure difference of 1 mm of mercury is 3.6 mm, a value little less than that in Tōkyō.

The constant increase of the mean level shows that the porous layer which feeds the well extends to some distant high places. The stopping of the flow may probably raise the level of the underground

water in these places, and consequently causes the steady increase of the level.

It is obvious that the daily change of the level is due to the pressure of the tidal motion in the Bay. In Negishi, a canal 20 m wide passes by the well, and its level is affected by the tide by about 1 m. But the comparison of the phase of the level change with that in the well showed that the level in the well was not connected with the canal water.

Since the level change in the well was reduced to about $\frac{1}{4}$ of its actual size, the effect of a small barometric change did not appear in the curves recorded on the cylinder. The curves are therefore very simple, showing distinctly the form of the ocean-tide. It is interesting to observe that the positions of the maxima and minima of the curves in Tōkyō and Yokohama fairly coincide with each other.

An experiment of the artificial pressure was also performed with the results given in the following table:

Pressure difference in mercury.	Ratio h/p (abs. value).
+ 0.78 mm	11.2 mm
— 0.51	11.5
— 1.02	13.2
— 3.91	13.4
— 5.30	13.6
+ 11.40	13.6

Thus the asymptotic value of the level change per 1 mm of mercury is again 13.6 mm. In the well, the level changed almost instantaneously by applying the pressure or the exhaustion.

Now the artificial pressure causes the level change of 13.6 mm for the pressure difference of 1 mm of mercury, while the atmospheric pressure only causes the level change of 3.6 mm for the same change of pressure. The earth crust in the neighbourhood of the well transmits therefore 74 % of the pressure acting on the surface to a layer which feeds the well.

When the upper part of the main tube was replaced by a glass tube and the motion of the meniscus followed by the eye, a minute fluctuation of the level was observed, indicating that the atmospheric pressure was varying.* The amplitude of the minute level change increased in windy weather; in a breezing day, level oscillations with the amplitude of 0.1–0.7 mm and with the period of 3–4 sec. were observed. In the experiment, the effect of aspiration was excluded by leading the mouth of the tube to a calm place by a lead tube.

Since the barometric oscillations of such a short period are extremely local, this change of the atmospheric pressure must have the same effect as the artificial pressure applied directly on the head of the water; that is, it will cause the level change of 13.6 mm by the pressure difference of 1 mm of mercury. The motion of the meniscus can also be magnified 10 times or more, by inclining the glass tube, so that the pressure change of 1 mm of mercury produces the motion of the meniscus by 136 mm or the more.

Artesian well in Yoshiwara.

The well in Yoshiwara in the province of Suruga is about 10 m higher than the sea level, and 3.3 km distant from the sea-coast; it is only 24 m deep and its wall consists of bamboo tubes. The well belongs to Mr. Kawashima, to whom my best thanks are due. The water was flowing out over the tube, and therefore the flow was stopped by making the head of water with a thick tube 20 cm in diameter, but the water only rose to a mean height of about 1 m above the earth surface and did not increase with time.

The arrangement used in the well was the same as in Tōkyō; the record was taken from 3rd to 21th of January in this year. The following is the result of observation.

* M. Toepler, Ann. der Phys. 12, 787, 1903.

(1) The daily level change (Fig. 9) is the exact copy of the tidal motion. Its amplitude is about 8–11 cm, and the phase of the level change coincides with that of the tide.

(2) The slow change of the barometric pressure does not seem to affect the level of the water.

(3) The effect of artificial pressure is the same as in the former two cases. The level changed almost instantaneously by the application of pressure or of exhaustion. The following table contains the result of observation :—

Pressure difference in mercury.	Ratio h/p (abs. value).
+0.97 mm	11.0 mm
+2.46	12.7
−0.89	11.6
−3.30	12.8
−5.03	13.5
−5.27	13.6

Thus in this well, we also observe a remarkable effect of the tidal pressure. Since the artificial pressure produces the level change of 13.6 mm by the pressure difference of 1 mm of mercury, whilst the slow barometric change does not cause any change of the level, it follows that the earth crust in the district transmits nearly all the pressure acting on the surface to a depth of about 30 m. To this inference, we may add that the district of Yoshiwara is formed of the deposition of the river Fuji.

It is interesting to observe that though the level of the well was not affected by the slow barometric change, we observed, in a windy weather, a minute level change of short periods in a vertical glass tube, jointed to the bamboo tube in the well. Thus we also see that the rapid fluctuation of the atmospheric pressure has the same effect as the pressure applied on the water-column. Hence such a well may conveniently be used for studying the barometric oscillations of short periods.

Artesian well in Ōkubo.

Ōkubo is a village on the slope of the Mount Fuji, 6 km distant from the sea-coast; the boring of the well is now going on. The well is at a place 230 m higher than the sea level; its depth is 110 m and its water level 38 m below the ground. It is fed with two water layers, one at 43 m and the other at 58 m; since the surface crust in the district consists of hard rocks, only the upper few meters of the well are protected with an iron tube.

The observations were taken with the same arrangement as in Tōkyō and continued only for 5 days, beginning from the first of January in this year. The results of observation were as follows:—

(1) The level constantly fell 11 cm during 5 days.

(2) In every 24 hours, we observe two maxima and minima of the amplitude of about 3 mm, their phases being opposite to those of the tide. The amplitude of the change becomes gradually less, as we recede from the time of conjunction.

(3) The barometric change does not seem to affect the level of the water.

(4) The effect of artificial pressure is the same as in the former cases, as shown in the following table.

Pressure difference in mercury.	Ratio h/p (abs. value).
–1.36 mm	13.4 mm
–4.28	13.5
+2.27	13.3
–6.32	13.6

When the pressure was applied or released, the level changed logarithmically with respect to time.

It is evident that the gradual falling of the level was due to the dry weather which prevailed on those days. On account of the small depth,

the effect of the barometric change was absent in the well ; hence the daily change of the level can not be explained by the daily barometric change ; moreover the phase of the level change is opposite to what is to be caused by the pressure change. It is not unconceivable that the tidal pressure would diminish the underground pressure in such high place by the strain of the hard surface crust, and so cause the reversal of the phase in the level change ; but the question of the tidal pressure in the well must be postponed to a future date, when we shall have a long series of observations.

Concluding remarks.

The fact that in each of the four wells, the pressure of 1 mm of mercury applied on the level of the water produces the level change of 13.6 mm shows the constancy of the pressure at an internal point in the well by compressing or exhausting the air above the level of the well ; that is, it indicates the existence of the air space, which we have already discussed. Hence we may infer that in every artesian well, the level of the water is held in a position by the equilibrium of two pressures — the atmospheric pressure and the underground pressure. If one of these pressures undergoes a change, a corresponding change of level is produced.

It was thought probable that this remark would apply even to common wells. That the level of a well does not change by gradually pumping out or in the water, furnishes us a verification of the above view. To test it directly, a well 4 m deep was dug and its well was protected with an iron tube 15 cm in diameter ; the water then rose to a height of 1.86 m below the ground. By changing the pressure above the water, the level slowly changed as in artesian wells. Reducing the pressure by 15.9 cm in mercury, the water just rose to the surface of the ground ; the ratio h/p then becomes 11.7 mm, which falls a little short of the desired value. But this difference may be explained by

the poor supply of water owing to the small depth of the well.

In connection with the above experiment, it was necessary to see, if the air may pass into a depth of a few meters through the soil (red clay) by the pressure above used. For this purpose, another well 2.5 m deep was dug, and its wall was likewise protected with an iron tube; the water did not spring. The experiment showed no trace of leakage when the said exhaustion was reached. It follows then that in common wells also, the atmospheric and the underground pressure are in equilibrium. But in most common wells, on account of their small depth, the change of the barometric pressure is almost transmitted through the soil, so that the level of the water is not sensibly affected by it.

The pressure at an internal point of the earth crust due to the pressure applied on the surface depends upon its depth as well as the nature of the crust. By the above consideration, the percentage reduction of the pressure at the point is found by simply observing the level change of a well due to the change of atmospheric pressure, if the well be so deep as to reach the point in question. It is very desirable to observe this reduction-factor in the different parts of the world.

From the daily change of the level observed in the three artesian wells, it is now clear that in the sea and also in the districts which are not far from the sea coast, the pressure of an internal point is considerably affected by the tidal motion. It seems also very probable that in our island, the underground pressure at any point is always changing by the tidal motion, if the depth of the point under consideration is comparable with the width of the island. But independently of such an assumption, it is highly interesting to investigate experimentally how far the tidal pressure extends into the inland.

In conclusion, the following remarks may not be out of place. Let it be supposed to be the case that the internal pressure undergoes the daily fluctuations by the tidal motion as well as the barometric change; such fluctuations of the underground pressure may give an

opportunity for the earthquakes to take place. Professor F. Ōmori* investigated the relation of the activity of earthquakes to the phase of the moon in the lunar day, to the season of the year, and to the change of barometric pressure. He found, in each case, a remarkable connection between them. If the curve of the activity of earthquakes be plotted against the lunar time, the earthquakes due to the daily barometric change of pressure will be equally distributed over the whole day. Thus the earthquakes due to the tidal effect is separated. In this way, Professor F. Ōmori found several maxima in the activity-curves for three stations in Japan, namely Nagoya, Nemuro, and Tōkyō. By smoothing these curves, he obtained two distinct maxima in each curve, which occur at about 5th and 17th hours of the lunar day, the time beginning with the upper culmination of the moon. In Nemuro, the second maximum is slightly displaced towards the earlier time. These positions of the maxima nearly coincide with those of the high water.

If the curve of activity be drawn with the solar time, the earthquakes due to the tidal effect will be equally distributed over the day. The effect of the daily barometric change of pressure on the activity will thus be separated. Professor Ōmori found a remarkable coincidence between the pressure and the activity of earthquakes, the high pressure generally corresponding to the maximum activity.

As regards the annual distribution of the earthquakes, he also found a good coincidence between the activity-curve and the pressure-curve, the maximum activity generally corresponding to the high pressure. But in some stations, the phenomenon is just reversed, the maximum activity occurring at the low pressure. It seems probable that this reversal arises from the difference of the structure of the crust in these districts; in one place, the increase of the atmospheric pressure may augment the instability of a strained portion, while in the other, its decrease may have the same effect. The activity of the

* F. Ōmori, Reports (Japanese) of the Earthquake Investigation Committee, Nos. 26, 30, and 32.

earthquakes must also be affected by the high tide in Spring, so that its activity is considerably large in Spring, as shown by Professor Ōmori.

Assistant Professor A. Imamura has investigated the synodic monthly distribution of the earthquakes, and found, in every case, two pairs of maxima, the one pair occurring at the days near conjunction and opposition, and the other at the days near 7th and 24th in each synodic month. The first pair occurs, when the tidal motion is maximum, that is, when the fluctuation of the internal stress due to the tide is maximum. The second pair of maxima occurs in the days, when the phase of the tidal pressure coincides with that of the barometric change; in this case, the fluctuations of the internal stress are also considerable. Thus the lunar effect on the activity of the earthquakes may be attributed to the tidal pressure.

The above consideration is also supported by the following remarks. The actual tidal motion at a station is more complex than to be judged from the phase of the moon; hence for studying the relation between the activity of earthquakes and the tidal motion, it is not convenient to draw the activity-curve against the lunar time. It is better to see, from the record of a tide-gauge in the station, in what phase earthquakes actually occurred, and to mark, in a figure of the tidal motion, the points having the same phases. In this way, Figs. 10, 11, 12 and 13, were obtained. These curves show that the activity of the earthquakes is maximum in high and low waters; there is another minor maxima in phases, where the variation of the tide is greatest. That the maximum activity occurs in high water as much as in low water is evident; for the earth crust is in equilibrium under the action of external pressures, and therefore an increase or decrease of the pressure acting on the surface may, in some cases, equally increase the unstability of a highly strained portion. Thus these positions of the maxima are consistent with the above view.

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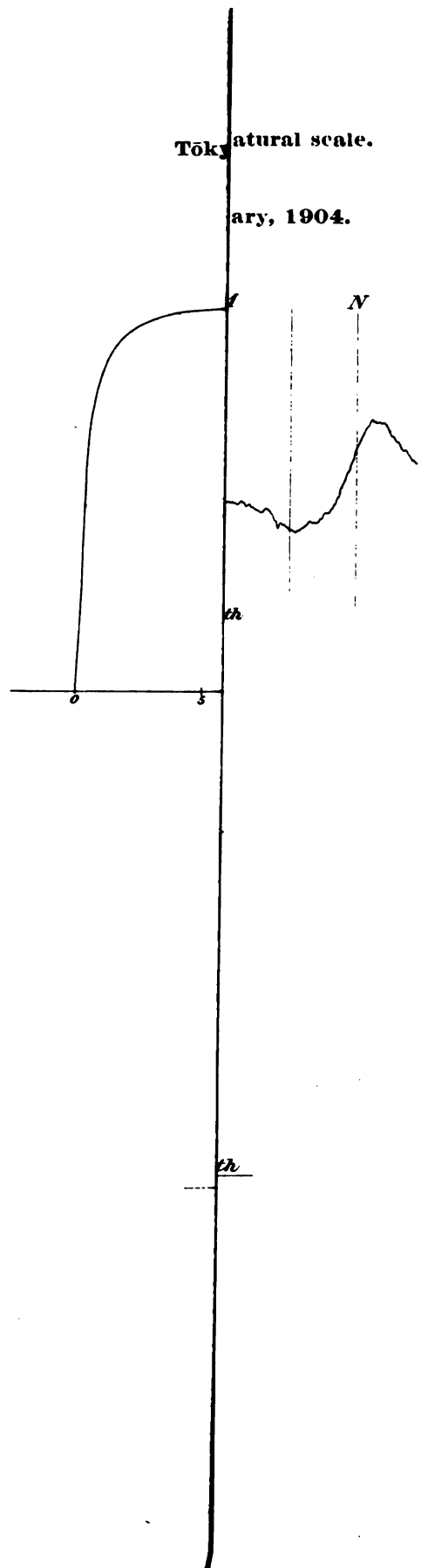




Fig. 11.
Earthquakes observed at Tōkyō, 1899.

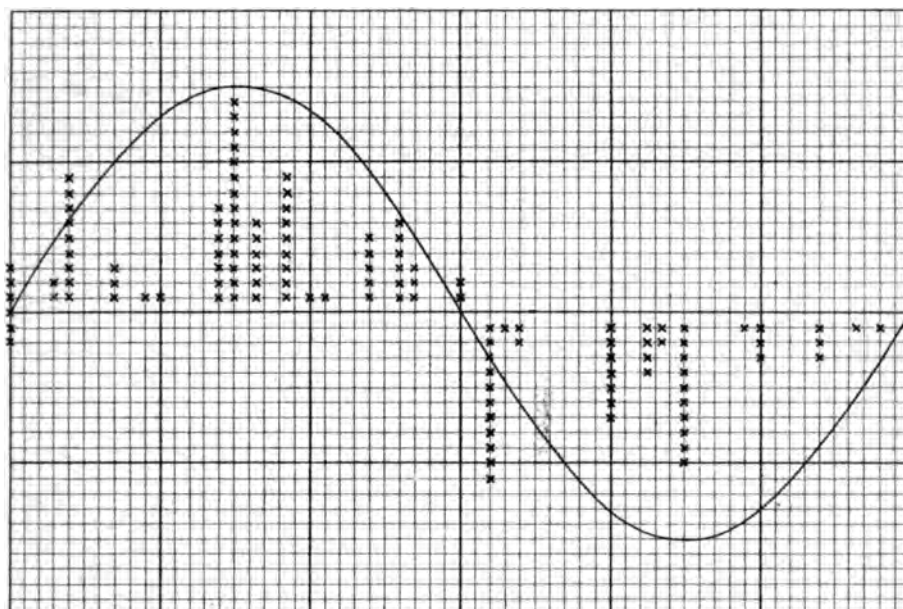


Fig. 10.
Earthquakes observed at Tōkyō, 1898.

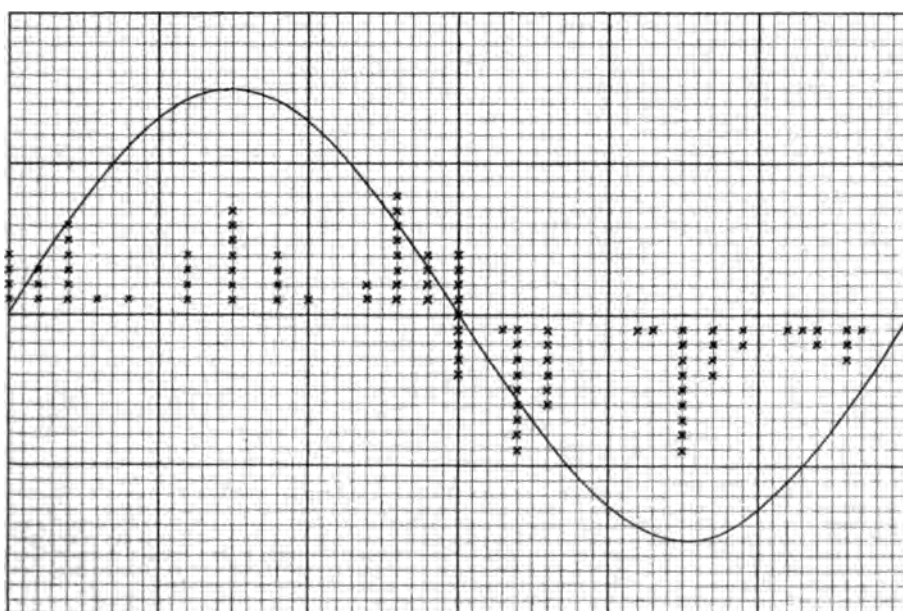


Fig. 12.
Distant earthquakes observed
at Tōkyō, 1900.

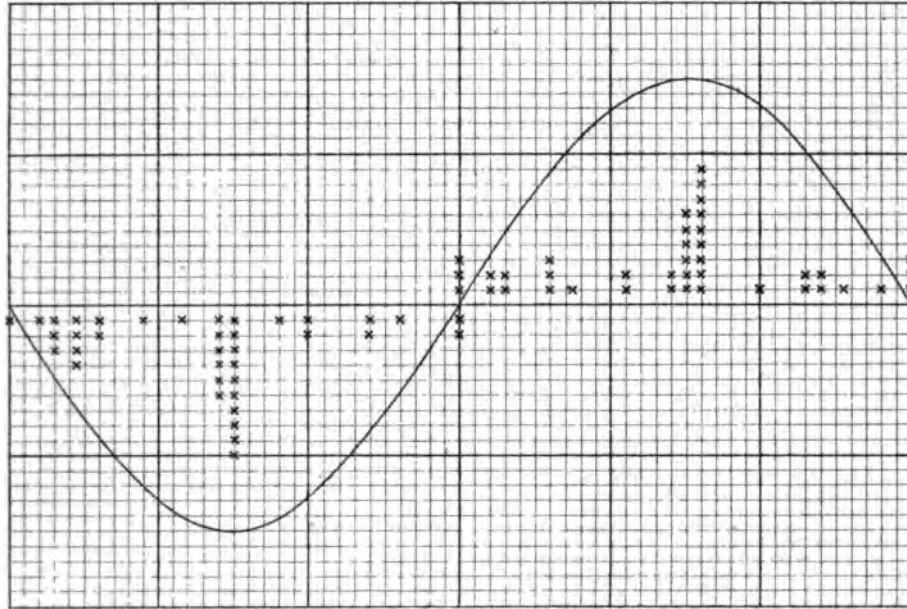
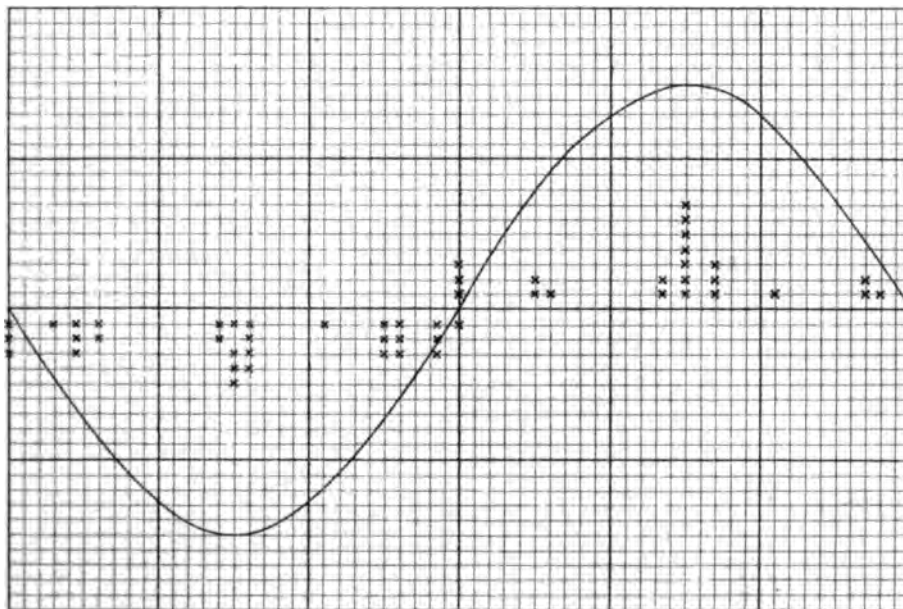


Fig. 13.
Earthquakes of submarine origin observed
at Tōkyō, 1900.





Note on the Seismic Triangulation in Tokyo.

By

A. IMAMURA, *Rigakushi,*

Extraordinary Member of the Imperial Earthquake
Investigation Committee.

With Plate XXIV.

In a former report on the seismic triangulation in Tokyo,¹ the present writer has given the transit velocity of the wave at the commencement of the principal portion of the earthquake motion, this wave being usually well defined so that it can easily be identified in the diagrams obtained at the different seismic stations. In the present note, I add the transit velocities of the other waves which have not formerly been discussed; namely, those of the preliminary tremor and the waves following the initial wave of the principal portion.

I. The preliminary tremor.

As it was difficult to identify the waves in this phase in the diagrams of the 8 earthquakes registered at the different stations,² the transit velocity has been determined according to the formula

$$\frac{1}{v} = \frac{1}{V} - \frac{t}{d},$$

where v and V represent the respective transit velocities of the initial waves of the preliminary tremor and principal portion, t the duration of the preliminary tremor, and d the epicentral distance. The result

1. The *Publications*, No. 7.

2. *Loc.*

is given in the following table, in which the duration of the preliminary tremor is taken from the diagrams given by one of the three Ewing type instruments.

Eqke. no.	Date.	t	d	v
		s	km	$\frac{\text{km}}{\text{s}}$
1	April 3, 1895.	2	110	3.5
2	Feb. 23, 1896.	18	160	5.3
3	March 6, 1896.	9	120	4.4
4	April 24, 1896.	8	70	5.4
5	Aug. 5, 1897.	14	450	3.7
6	Aug. 16, 1897.	12	300	3.8
7	Feb. 13, 1898.	7	60	6.0
8	July 12, 1898.	3	80	3.8

The initial wave in the registers of the eqkes. Nos. 1, 5, 6, and 8 is too large and does not probably represent the real commencement of the earthquake motion. The rocks of Archean formation, which have a transit velocity of seismic waves as high as 6-7 km. per sec., may form a part of the path for the wave in the present discussion.

II. *The principal portion.*

The eqke. no. 7 was one which gave the most appropriate diagrams for the deduction of the transit velocities of the successive waves of the principal portion. The waves F-G and P-S in E-W component, and h-i and o-s in N-S one being very distinct, I have divided the principal portion into three successive phases, each of which began with one of the above-mentioned waves. (See the accompanying figure.) The result is given in the following tables.

E-W COMPONENT.

Phase.	Wave.	Time of arrival.			
		Hongo.	Hitotsubashi.	Astro. Obs.	Komatsugawa.
I	A	^s 7.57	^s 8.22	^s 8.83	^s 8.87
	B	8.19	8.82	—	9.73
	C	8.50	9.12	—	—
	D	8.91	9.60	—	—
	E	9.49	10.27	—	11.09
II	F	10.17	11.00	—	11.70
	G	10.79	11.57	—	12.29
	H	11.63	12.18	—	12.88
	I	11.87	12.50	—	13.78
	J	12.19	12.90	—	14.09
	K	12.63	13.52	—	14.88
	L	13.45	14.12	—	15.45
	M	13.79	14.48	—	16.00
	N	14.15	14.87	—	16.37
	O	14.37	15.23	—	16.70
III	P	14.85	15.77	—	17.41
	Q	15.22	16.08	—	17.91
	R	15.66	16.51	—	18.46
	S	16.24	17.28	—	19.23
	T	17.15	18.21	—	20.60
	U	17.59	18.74	—	—
	V	18.28	19.26	—	—
	W	19.26	20.30	—	21.90

N-S COMPONENT.

Phase.	Wave.	Time of arrival.			
		Hongo.	Hitotsubashi.	Astro. Obs.	Komatsugawa.
I	a	7.53	8.17	8.62	8.90
	b	7.87	8.52	9.00	9.26
	c	8.59	9.23	10.00	10.02
	d	9.19	9.79	10.77	10.98
	e	9.55	10.11	11.41	11.51
	f	9.86	10.50	11.79	12.05
	g	10.65	11.03	12.61	—
II	h	11.07	11.49	13.05	—
	i	11.33	11.93	13.67	13.62
	j	11.81	12.49	14.19	14.10
	k	12.13	12.83	14.41	—
	l	12.82	13.45	15.02	15.14
	m	13.53	14.30	—	15.86
	n	14.00	14.62	—	16.50
III	o	14.50	15.50	16.80	17.10
	p	14.88	15.90	17.62	17.52
	q	15.28	16.32	18.00	17.97
	r	15.91	16.77	18.21	18.55
	s	16.24	17.22	18.65	—
	t	16.79	18.15	19.28	19.30
	u	17.24	18.56	19.75	19.88
	v	17.64	18.97	20.10	—
	w	18.37	19.83	—	20.91

The following table gives for each phase the mean times of arrival of the successive waves at the 3 local stations, referred to the time of arrival of the same waves at Hongo.

Station.	E-W component.			N-S component.			Mean.		
	I	II	III	I	II	III	I	II	III
Hitotsubashi.	^s 0.67	^s 0.73	^s 0.99	^s 0.59	^s 0.63	^s 1.15	^s 0.62	^s 0.69	^s 1.08
Astronomical Obs.	1.26	—	—	1.69	2.23	2.49	1.52	2.23	2.49
Komatsugawa.	1.38	1.91	2.76	1.69	2.34	2.61	1.62	2.05	2.68

From these data, it will be seen that the directions of propagation of the different phases of the earthquake motion coincided roughly with one another, the approximate value being N25°W. The transit velocities of the various phases thus come out to be 3.0, 2.3, and 1.8 km. per sec. Each of these different values may probably relate to one of the strata which are supposed to lie near the earth's surface parallel to the latter, the terms corresponding to the superficial layer, into which the waves propagated through the assumed stratum refract to reach our observing stations, being eliminated in the process of taking the difference of the times of arrival.

The different phases discussed in the present note may possibly have certain relation with the three phases following the most active part of the principal portion of large distant earthquakes.

May 24, 1904.

Seismological Institute.





On the transit velocity of the earthquake motion originating at a near distance.

By

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Extraordinary Member of the Imperial Earthquake
Investigation Committee.**

With Plates XXV–XXVI.

I. Introduction.

The assumption of the existence of a stratum of the quickest earthquake propagation near the earth's surface parallel to the latter is very important in the study of the mode of propagation of the seismic motion. In fact, the linear relation which exists between the arcual epicentral distance of a distant station and the time taken in transit by the 1st preliminary tremor is well explained by considering the depth of the stratum to be a few hundred kilometres.¹

It is a well-known fact that the mean velocity between the *origin* and a *near station* is comparatively small, becoming larger with the increase of the distance. For instance, the Kyushu, Formosa, and Manila earthquakes, which occurred in 1899–1902, had the velocities of 8.2, 10.6, and 10.9 km per sec. for the epicentral distances of 900, 2200, and 3050 km. respectively.² To see how the first phase is propagated from a *near station* to *another* in similar case, I have first examined the observations at Tokyo and Osaka of the earthquakes, which originated in NE Japan or in Kyushu, and obtained a transit

¹ The *Publications*, No. 16, p. 116.

² See Dr. Omori: The *Publications*, No. 13, p. 141.

velocity as high as 12 km. per sec., the result of similar examination made afterwards of the observations at the Mizusawa Astronomical Observatory being nearly the same. It must be remarked that, the origin of each earthquake having been comparatively near the observing stations and approximately in the direction of the straight line connecting the latter, the difference of the epicentral distances is but little affected by an inaccurate determination of the epicentre, whether the path be actual or chordal.

The earthquakes taken into consideration are given in the following table:—

Earthquake No.	Date.	Time of occurrence. at epicentre.	Epicentre.	
			Latitude.	Longitude.
1902.				
1	Jan. 29.	23 ^h 24 ^m 50 ^s	34.5 N	139.8 E
2	Jan. 30.	23 0 0	41.0	142.5
3	Jan. 31.	10 41 30	41.5	142.5
4	Feb. 21.	0 37 40	40.8	142.8
5	May 2.	20 31 0	40.5	144.0
6	May 8.	11 19 0	30.7	131.6
7	May 28.	18 1 40	42.8	144.8
8	June 13.	9 21 20	42.7	144.3
9	June 23.	7 42 20	35.5	133.8
10	July 1.	17 16 20	40.0	144.0
11	July 8.	23 5 —	41.5	142.5
12	July 10.	19 56 20	41.7	142.0
13	Aug. 3.	10 40 —	42.5	146.5
14	Aug. 7.	18 19 —	39.8	143.7
1903.				
15	March 21.	19 35 50	33.7	132.0
16	April 1.	23 8 30	39.0	142.0
17	Aug. 10.	13 38 —	36.0	137.1
18	Aug. 10.	13 45 —	36.0	137.1
19	Aug. 14.	0 46 —	42.8	141.8
20	Oct. 11.	1 41 0	32.3	132.0
21	Dec. 3.	17 52 40	32.0	132.0
1904.				
22	March 18	22 — —	42.7	144.3
23	April 13	14 37 40	38.7	142.0
24	May 27	5 40 0	35.0	139.6

The positions of the epicentres and times of commencement at the latter were determined from the result of instrumental observations at the Meteorological Stations and observations of the seismic intensity by the meteorological reporters in the different parts of the country. The observations depending on the 1st category are given in the *Publications*, No. 16, or in the appendix to the present note. The numbers of observations of the 2nd category were 205 and 156 in Eqkes. Nos. 2 and 3 respectively. These two earthquakes are specially discussed later on.

II. Observations at Tokyo and Osaka.

The diagrams examined were given by Omori's H. P. Seismographs at the Seismological Institute and Osaka Meteorological Observatory. The following is the list of the instruments which gave the Tokyo register.

Instrument.	Orientation.	Magnification.	Free vibration period.
No. 1.	E-W component.	10	^{s.} 26
A	Do.	15	62
B	N-S component.	10	30

The instrument at Osaka was less sensitive and had a magnification of 6 times and a period of 25 sec.

The time which is marked every minute on the smoked paper, is kept at Tokyo by a chronometer, but at Osaka by a clock whose daily change of clock rate amounted seldom to 20 sec., being commonly one-half of the latter. The clock and chronometer are daily compared with the standard time at noon, the former by means of an electric signal sent directly from the Tokyo Astronomical Observatory, but the latter indirectly by the report of a cannon at a distance of 2.3 km.

Of the 41 earthquakes which were first taken into examination, the Osaka instrument did not record the time ticks in 20 cases, and gave 6 seismograms, 4 of which were too minute and the others were masked by pulsatory oscillations; besides, the correction of the clock was so uncertain in 2 cases that a reliable clock rate could not be obtained. In all, there were 13 earthquakes which were recorded tolerably well at the two stations.

Let P_1 , P_2 , and P_3 represent the initial waves of the 1st and 2nd preliminary tremors and principal portion, and V_1 , V_2 , and V_3 their respective transit velocities. The latter were calculated according to the formula

$$\text{Velocity} = \frac{d' - d}{t' - t},$$

where d and d' indicate the arcual epicentral distances of the two observing stations, and t and t' the times of arrival of each phase at the respective stations. The result is given in the following table.

Eqke. no.	Time of com- mencement at Tokyo.	Epicentral distance.			Diff. of times of arrival of P ₁ .	V ₁ $\frac{\text{km}}{\text{s}}$	Duration.				Diff. of times of arrival of P ₂	V ₂ $\frac{\text{km}}{\text{s}}$	Diff. of times of arrival of P ₃ .	V ₃ $\frac{\text{km}}{\text{s}}$
		Neuer station.	Further station.	Diff.			Tokyo.		Osaka.					
							P ₁ -P ₂	P ₂ -P ₃	P ₁ -P ₂	P ₂ -P ₃				
2	h m s 23 1 43	622	927	312	s 26	$\frac{\text{km}}{\text{s}}$ 12.0	s 21	s 3	s 48	s 65	s 53	$\frac{\text{km}}{\text{s}}$ 5.9	s 82	3.8
3	10 42 58	685	969	284	23	12.4	19	52	37	40	41	6.9	69	4.1
4	0 39 13	625	930	305	31	9.8	23	45	43	76	51	6.0	82	3.7
5	20 32 3	648	1005	357	33	10.8	29	56	48	89	52	6.9	85	4.2
7	18 3 43	898	1205	307	27	11.4	36	72	66	99	54	5.7	81	3.8
10	17 17 27	604	992	388	33	11.8	32	41	51	71	49	7.9	79	4.9
11	23 7 36	685	969	284	19	15.0	28	36	40	63	40	7.1	67	4.2
13	10 43 17	951	1285	334	26	12.9	78	72	103	99	53	6.3	80	4.2
14	18 20 50	571	917	346	28	12.4	27	35	48	68	49	7.1	80	4.3
15	19 37 36	341	743	402	35	11.5	41	56	18	18	58	6.9	96	4.2
16	23 9 24	324	688	364	24	15.2	20	23	48	56	52	7.0	85	4.3
20	1 42 38	420	810	300	36	10.8	56	69	27	30	56	7.0	95	4.1
21	17 54 38	442	826	384	28	13.7	52	79	28	36	52	7.4	95	4.0
Mean.	—	601	944	343	28.4	12.1	36	52	47	65	51	6.7	83	4.1

The values thus deduced do not much differ from those which are generally obtained in cases of large distant earthquakes, the formula adopted being the same.

Let us next compare these velocities with those which are obtained according to the formula

$$\text{Velocity} = \frac{d}{t - t_0},$$

where t_0 indicates time of commencement at epicentre, which was estimated with tolerable accuracy for the preceding earthquakes except Nos. 11, 13, and 14. In the following table only the mean values are given.

Place.	Epicentral distance.	Time taken in transit.			Transit velocity.		
		P_1	P_2	P_3	V_1	V_2	V_3
Tokyo.	679km	91*	124*	177*	7.5 $\frac{\text{km}}{\text{s}}$	5.5 $\frac{\text{km}}{\text{s}}$	3.8 $\frac{\text{km}}{\text{s}}$
Osaka.	792	101	142	204	7.9	5.6	3.9

The difference of the values of V_1 due to the two different methods may be explained, as has been noted previously, by assuming the stratum of the quickest propagation to have a depth of a few hundred kilometres. For the seismic motion radiating from the origin, which may be situated comparatively near the earth's surface, is propagated directly to observing station in the epicentral district, while the initial wave observed at a more distant station may be the wave propagated from the origin first downward to the stratum of the quickest propagation, next through that stratum to a position near the observing station, and then refracting to the latter. In so supposing, the transit velocity estimated according to the 1st formula relates particularly to the assumed stratum, the term depending on the depth being eliminated in the process of taking the difference. If the velocity determined according to the 2nd formula represent the mean value between the origin and a distant observing station, it seems more proper to introduce in the term of epicentral distance a correction, which, roughly

speaking, is equal to double of the distance between the seismic focus and the stratum of the quickest propagation.

Assuming the state of propagation of the 1st preliminary tremor as discussed above, the time which would have been taken by the wave-front in its transit from the seismic focus to the assumed stratum is calculated in the preceding 10 earthquakes to have been 20 sec. on the average. In the Kyushu, Formosa, and Manila earthquakes, previously cited, the times amount to 23, 25, and 31 sec. respectively. For the Aomori earthquake of Aug. 9, 1901, in which the focal depth was probably very shallow,¹ the value amounts to 60 sec. The time calculated in such a way may probably be used for the determination of the depth of the seismic focus and the stratum of the quickest propagation.

The path of P_3 seems, as usually accepted, to be superficial, for the velocities deduced by the two different methods do not much differ from each other. As regards P_2 , the path may be inferred to lie between the two others.

III. Observations at Tokyo and Mizusawa.

The instruments at Mizusawa consist of a pair of Omori's H. P. Seismographs, that which registers E-W component motion being of the same type as that at Osaka but so adjusted as to have a free vibration period of 13 sec, while the other which records N-S component motion being of the same type and about equal period as the Tokyo instrument No. 1.²

The clock keeping the time tick was at first compared with the standard chronometer at the start and end of each smoked paper which lasts about 24 hours; but since the end of 1902, it was more frequently compared so that an accurate clock correction could be obtained whenever earthquake occurred. Hence, in the calculation of

¹ The *Publications*, No. 16. p. 75.

² See also Annual Report of the Meteorological Observations at Mizusawa for the year 1903.

the mean values of transit velocity, the weight of the data relating to the former epoch is assumed to be one-half of that relating to the latter.

Many earthquakes, which originated near one of our stations, have been grouped against those which originated at distances greater than 400 km. The result for the different groups will be understoed from the following tables.

OBSERVATIONS OF NEARER EARTHQUAKES.

Eqke. no.	Epicentral distance.			Time of com- mencement at Tokyo.	Diff. of times of arrival of P ₁	V ₁ km s
	Nearer station.	Further station.	Difference.			
	km	km	km	h m s	s	
1	139	529	390	23 25 10	39	10.0
2	237	622	385	23 1 43	45	8.6
3	287	685	398	10 42 58	43	9.3
4	233	625	392	0 39 13	41	9.6
5	287	648	361	20 32 3	41	8.8
9	22	420	398	7 42 39	45	8.8
10	264	604	340	17 17 27	45	7.6
11	287	685	398	23 7 36	27	14.7
12	294	694	400	19 57 53	35	11.4
14	235	571	336	18 20 50	44	7.6
16	148	324	176	23 9 24	13	13.5
17	243	496	253	13 40 9	27	9.4
18	243	496	253	13 46 12	27	9.4
23	88	388	300	14 38 30	34	8.8
24	92	479	387	5 40 34	39	9.9
Mean.	196	522	327	—	34	9.6

OBSERVATIONS OF REMOTER EARTHQUAKES.

Eqke. no.	Epicentral distance.			Time of com- mencement at Tokyo.	Diff. of times of arrival of P ₁	V ₁ km s
	Nearer station.	Further station.	Difference.			
	km	km	km	h m s	s	
6	944	1275	331	11 21 19	28	11.8
7	510	838	388	18 3 43	39	9.9
8	475	871	396	9 23 39	34	11.6
13	586	951	365	10 43 17	32	11.4
15	743	1015	272	19 37 36	21	13.0
19	510	838	388	0 48 8	25	15.5
20	810	1120	310	1 42 38	22	14.1
22	475	871	396	22 48 33	36	11.0
Mean.	633	984	351	—	28.4	12.4

Thus we arrive at nearly the same result as that deduced from the observations at Tokyo and Osaka, the value relating to the earthquakes which originated in near distances approximating to that calculated according to the 2nd formula in the previous case.

IV. Earthquakes of Jan. 30 and 31, 1902.

The 1st preliminary tremor of Eqkes. Nos. 2-3 were also recorded at several seismic stations in Europe and other parts of the world. The following is the result of those observations.

Eqke. No. 2.

Place of observation.	Epicentral distance.	Time taken in transit by P_1 .	Place of observation.	Epicentral distance.	Time taken in transit by P_1 .
		m			m
Mizusawa.	2.1	1.0	Nikolajew.	72.7	11.5
Tokyo.	5.6	1.7	Hamburg.	76.9	11.9
Osaka.	8.4	2.2	Strassburg.	82.0	12.2
Irkutsk.	28.1	5.6	Trieste.	82.0	11.8
Calcutta.	49.0	8.0	Pola.	82.6	12.6
Taschkent.	53.3	9.8	Padova.	83.0	12.7
Batavia.	57.3	10.0	Shide.	83.4	12.3
Madras.	60.9	10.6	Firenze.	84.5	11.4 (?)
Bombay.	62.8	10.1	Roma.	85.6	13.0
Victoria.	62.8	10.2	Rocca di Papa.	85.6	13.2
Jurjew.	67.3	11.8	Ischia.	86.3	12.9
Tiflis.	68.8	11.4	Catania.	88.0	13.0

Eqke. No. 3.

Place of observation.	Epicentral distance.	Time taken in transit by P_1 .	Place of observation.	Epicentral distance.	Time taken in transit by P_1 .
		m			m
Mizusawa.	2.6	0.8	Nikolajew.	72.3	11.5
Tokyo.	6.2	1.5	Hamburg.	76.6	11.7
Osaka.	8.7	1.9	Strassburg.	81.5	12.3
Irkutsk.	27.8	5.3	Trieste.	81.6	12.1
Taschkent.	53.1	8.4	Shide.	82.7	11.6
Bombay.	62.5	10.1	Firenze.	84.1	11.1 (?)
Jurjew.	66.8	10.6	Roma.	85.2	12.8
Tiflis.	68.5	11.2			

The mode of propagation of the earthquake motion may be understood from the graphical representation given in Fig. 1. The curves in the figure have been drawn according to the following method:— Marking down as usual on a section paper so many points corresponding to the different sets of the epicentral distance (x) and the time taken in transit (y), a continuous free-hand line was drawn connecting the 4 left-hand points and thence a straight line determined by the method of Least Squares from the 5 points for Irkutsk, Calcutta, and the 3 mean places for the stations whose epicentral distances are 53° – 63° , 67° – 77° , and 82° – 88° ¹ in Eqke. No. 2, and from the 4 points for Irkutsk, Taschkent, and the 2 mean places for the stations whose epicentral distances are 62° – 77° and 81° – 86° ² in Eqke. No. 3. The linear relation seems to hold approximately for a distances as near as 10° , but the observations at comparatively near distances having been scanty, this part of investigation must be reserved for a future occasion.

The transit velocity comes out from the above mentioned straight line to be 14.3 and 14.1 km. per sec. in Eqkes. Nos. 2 and 3 respectively. These values are nearly equal to those obtained by Prof. Omori as a result of his more recent investigation.³

July 26, 1904.

Seismological Institute, Tokyo Imp. Univ.

¹⁻² Firenze is omitted.

³ Prof. Omori: *The Publications*, No. 13.

APPENDIX. EARTHQUAKE OBSERVATIONS AT THE METEOROLOGICAL OBSERVATIONS.* (THE TIMES ARE GIVEN IN THE FIRST NORMAL JAPAN TIME).

Eqke. No. 1. Jan. 29th 1902; 23h.

Mera.	... 25 ^m 0 ^s .	Weak.	Gentle.
Yokosuka.	.. 25 30.	Do.	Duration long.
Tokyo.	... 25 9.	Slight.	
Kanayama.	.. 25 10.	Do.	Duration short.
Maebashi	.. 25 15.	Do.	
Mito ..	... 25 42.	Do.	Gentle.
Choshi.	... 25 45.	Do.	Duration short.
Nagano.	.. 26 0.	Do.	
Kumagae	... 26 28.	Do.	
Miyako.	... 27 15.	Do.	Gentle.
Matsumoto	.. 27 55.	Do.	
Akita.	... 27 58.	Do.	
Fukushima.	... 30 54.	Do.	
Utsunomiya.	... 34 48.	Do.	Gentle.

Eqke. No. 7. May 28th 1902; 18h.

Kushiro.	... 1 ^m 53 ^s .	Strong (rather violent).	Sharp, houses shaken.
Tokachi.	... 2 15.	Weak.	Sharp.
Nemuro.	... 1 18.	Weak (rather slight).	Duration long.
Abashiri.	... 1 5.	Slight.	
Sapporo.	... 2 50.	Do.	Gentle.
Aomori.	... 3 6.	Do.	Sharp.
Miyako.	... 3 12.	Do.	{ Sharp, accompanied by vertical movement.
Wajima.	... 4 8.	Do.	
Mito.	... 4 30.	Do.	Sharp.
Ishinomaki.	... 3 10.	Slight (unfelt).	
Fukushima.	... 4 12.	Do.	

* Observations of Eqkes. Nos. 2, 3, 4, 5, 6, 8, and 10 are given in the *Publications*, No. 16.

Akita. ... 4 47. Do.
 Kumagae. ... 5^m11^s. Do.
 Tokyo. ... 5 20. Do.

Eqke. No. 9. June 23rd 1902; 7h.

Yokohama	.. 42 ^m 58 ^s .	Strong (rather weak).	{ Sharp, accompanied by vertical movement, houses shaken.
Tokyo.	... 42 20.	Weak.	
Yokosuka.	... 42 35.	Do.	{ Sharp, accompanied by vertical movement.
Kumagae.	... 42 40.	Do.	
Mito.	... 42 40.	Do.	Do.
Numazu.	... 43 40.	Do.	Do.
Mera.	... 45 40.	Do.	Houses shaken.
Choshi.	... 40 0.	Weak (rather slight).	{ Accompanied by earth- quake sound.
Kofu.	... 43 11.	Do.	
Nagano.	... 42 58.	Slight.	Duration long.
Utsunomiya.	... 44 20.	Do.	Gentle.
Wajima.	... 45 20.	Do.	
Matsumoto.	... 42 17.	Slight (unfelt).	Duration long.
Maebashi.	... 43 10.	Do.	
Fukushima.	... 43 11.	Do.	
Nagoya.	... 43 17.	Do.	Gentle.
Iida.	... 43 24.	Do.	
Hikone.	... 43 40.	Do.	
Ishinomaki.	... 43 49.	Do.	
Fukui.	... 44 0.	Do.	
Yagi.	... 44 45.	Do.	
Gifu.	... 47 23.	Do.	

Eqke. No. 11. July 8th 1902; 23h.

Tokachi.	... 6 ^m 0 ^s .	Weak.	Gentle.
Hakodate.	... 5 13.	Weak (rather slight).	Sharp.
Aomori.	... 8 42.	Do.	Windows rattled.
Miyako.	... 3 39.	Slight.	

Sapporo. ...	5 39.	Do.,	
Ishinomaki. ...	7 ^m 29 ^s .	Do.	
Akita. ...	7 41.	Do.	
Nemuro. ...	7 56.	Do.	Gentle.
Wajima. ...	8 23.	Slight.	
Kumagae. ...	4 12.	Slight (unfelt).	
Mito. ...	8 0.	Do.	
Tokyo. ...	8 36.	Do.	
Yokohama. ...	9 29.	Do.	Gentle.

Eqke. No. 12. July 10th 1902; 19h.

Hakodate. ...	56 ^m 35 ^s .	Weak (rather slight).	Sharp.
Miyako. ...	55(?)38.	Slight.	
Aomori. ...	57 6.	Do.	Sharp.
Nemuro. ...	57 27.	Do.	Gentle.
Wajima. ...	58 12.	Do.	
Sapporo. ...	58 30.	Do.	Gentle.
Akita. ...	57 30.	Slight (unfelt).	
Fukushima. ...	57 55.	Do.	
Tokyo. ...	59 30.	Do.	
Mito. ...	60 27.	Do.	

Eqke. No. 13. Aug. 3rd 1902; 10h.

Nemuro. ...	38 ^m 0 ^s .	Slight.	Gentle.
Fukushima. ...	42 40(?).	Slight (unfelt).	
Kanayama. ...	44 55.	Do.	
Akita. ...	47 36(?).	Do.	

Eqke. No. 14. Aug. 7th 1902; 18h.

Aomori. ...	19 ^m 17 ^s .	Weak (rather slight).	Gentle.
Wajima. ...	21 6.	Slight.	
Akita. ...	18 52.	Slight (unfelt).	
Kanayama. ...	20 13.	Do.	
Ishinomaki. ...	21 37.	Do.	

Mito. ... 22^m 3^s. Do.
Tokyo. ... 22 18. Do.
Iida. ... 23 5. Do. Gentle.

Eqke. No. 15. March 21st 1903; 19 h.

Kure.	...	36 ^m 10 ^s .	Strong.	
Ashizurizaki.	...	35 0.	Strong (rather weak).	Sharp, houses shaken.
Oita.	...	35 38.	Do.	{ Accompanied by vertical movement, clocks stopped.
Murotozaki	..	35 40.	Do.	Houses shaken.
Niihama	...	36 6.	Do.	Duration long.
Hiroshima	...	36 25.	Do.	Windows rattled.
Miyazaki...	...	37 0.	Do.	Sharp, houses shaken.
Tadotsu	...	41 58.	Do.	{ Accompanied by vertical movement, houses shaken.
Hamada	...	32 0.	Weak.	Houses shaken.
Ajino	..	32 3.	Do.	Clocks stopped.
Kochi	...	35 7.	Do.	Duration long.
Matsuyama	...	35 50.	Do.	{ Accompanied by vertical movement, houses shaken.
Sakai	...	36 0.	Do.	Houses shaken.
Besshi	...	36 0.	Do.	{ Accompanied by earthquake sound, houses shaken.
Okayama	...	36 25.	Do.	Houses shaken.
Kyoto	...	37 10.	Weak (rather slight).	Gentle.
Kumamoto	...	37 6.	Do.	Duration long.
Miyazu	...	37 10.	Do.	Do.
Fukuoka	...	37 20.	Do.	Do.
Saga	...	37 25.	Do.	Windows rattled.
Shimonoseki	...	37 32.	Do.	{ Accompanied by vertical movement, houses shaken.

Tokushima	...37 ^m 0 ^s .	Slight.	
Kagoshima	...37 4.	Do.	Gentle.
Fukui	... 37 15.	Do.	Duration long.
Hikone	...36 35.	Slight (unfelt).	Sharp.
Osaka	...37 17.	Do.	Gentle.
Iida	... 52 35.	Slight.	

Eqke. No. 16. April 1st 1903 ; 23 h.

Ishinomaki	... 8 ^m 57 ^s .	Weak.	Houses shaken.
Kanayama	... 8 37.	Weak (rather slight).	Duration short.
Miyako	... 6 1.	Slight.	Duration long.
Fukushima	... 8 38.	Do.	
Yokohama	... 9 52.	Do.	Gentle.
Kumagae	... 8 51.	Slight (unfelt).	
Matsumoto	... 8 53.	Do.	
Mayebashi	... 9 24.	Do.	
Yamakata	... 9 25.	Do.	
Choshi	... 9 57.	Do.	
Tokyo	...10 0.	Do.	
Iida	... 10 8.	Do.	Sharp.
Utsunomiya	...10 53.	Do.	
Aomori	... 11 15.	Do.	
Kinkasan	...12 30.	Do.	Duration short.

Eqke. No. 17. Aug. 10th 1903 ; 13 h.

Takayama	...37 ^m 35 ^s .	Weak (rather slight).	{ Sharp, accompanied by earthquake sound, houses shaken.
Kyoto	...34 19.	Slight.	
Fushiki	...39 40.	Slight (unfelt).	Gentle.
Katsumoto	...40 4.(?)	Slight.	
Hikone	...40 12.	Do.	Gentle.
Tsu	... 40 15.	Do.	

Tokyo	...	...41 ^m 0 ^s .	Slight.
Iida	..	...41 48.	Do.
Nagoya	...	...39 42.	Slight (unfelt).
Fukui	...	.. 41 0.	Do.
Kobe	...	.. 41 7.	Do.

Eqke. No. 18. Agu. 10th 1903; 13 h.

Takayama	...48 ^m 52 ^a .	Weak (rather slight).	Sharp.
Wajima	 46 20.	Slight.	Duration short.
Tokyo	46 35.	Slight (unfelt).	
Fushiki	 47 28.	Slight.	
Nagoya	 45 47.	Slight (unfelt).	
Iida	 46 10.	Do.	
Matsumoto	...46 25.	Do.	

Eqke. No. 19. Aug. 14th 1903; 0 h.

Kushihiro ...	...46 ^m 5 ^s .	Strong (rather weak).	Duration short.
Tokachi ...	.48 30.	Weak (rather slight).	Sharp.
Wajima ...	..47 10.	Slight.	Gentle.
Nemuro ...	.47 29.	Do.	Do.
Hakodate.	.. 48 5.	Do.	Do.
Ishinomaki.	.49 0.	Slight (unfelt).	
Mito. ...	.. 50 2.	Do.	Gentle.
Aomori. ...	.. 50 13.	Do.	

Eqke. No. 20. Oct. 11th 1903; 1h.

Toizaki.		37 ^m 25".	Strong.	Sharp, houses shaken.
Miyazaki.	..	41 19.	Do.	{ Sharp, accompanied by vertical movement.
Kagoshima.	..	41 30.	Weak.	Houses shaken.
Oita.	..	39 0.	Do.	Clocks stopped.
Matsuyama.	..	52 22.	Slight.	{ Accompanied by verti- cal movement.

Kumamoto.	...41 ^m 42".	Slight (unfelt).	Duration long.
Yagi.	...42 52.	Do.	
Fukuoka...	...44 50.	Do.	

Eqke. No. 21. Dec. 3rd 1903; 17h.

Miyazaki.	...53 ^m 4".	Weak.	Houses shaken.
Kagoshima.	...52 45.	Weak (slight).	Do.
Oshima.	...52 40.	Slight (unfelt).	Gentle.
Kumamoto.	...53 40.	Do.	
Oita.	...52 45.	Slight.	

Eqke. No. 22. March 18th 1904; 22h.

Nemuro.	...24 ^m 32".	Weak.	{ Liquid in vessels over- flowed.
Akita.	...44 52.	Do.	Duration long.
Aomori.	...45 1.	Do.	Windows rattled.
Kushiro.	...49 40.	Do.	Clocks stopped.
Tokachi.	...54 12.	Do.	Houses shaken.
Abashiri.	...44 40.	Weak (rather slight).	{ Accompanied by earth- quake sound.
Ishinomaki.	...57 31(?)	Do.	
Shanna.	...44 50.	Slight.	Gentle.
Kumagae.	...45 12.	Do.	Duration long.
Tokyo.	...46 15.	Do.	Gentle.
Nagano.	...46 40.	Slight (unfelt).	Duration long.
Iida.	...46 53.	Do.	Gentle.
Maebashi.	...47 31.	Do.	
Matsumoto.	...47 48.	Do.	Gentle.
Miyako.	...43 56.	Slight.	{ Accompanied by earth- quake sound.
Hakodate.	...45 6.	Do.	
Mito.	...45 0.	Do.	

Eqke. No. 23. April 13th 1904; 14h.

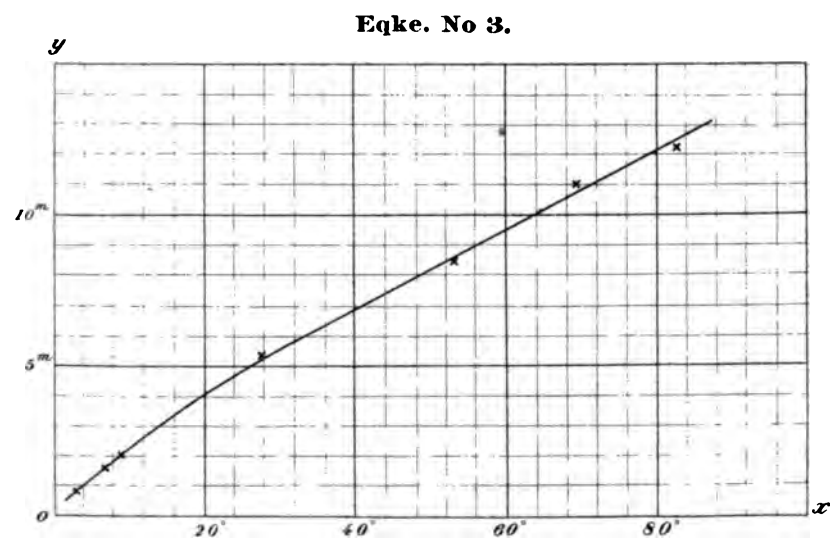
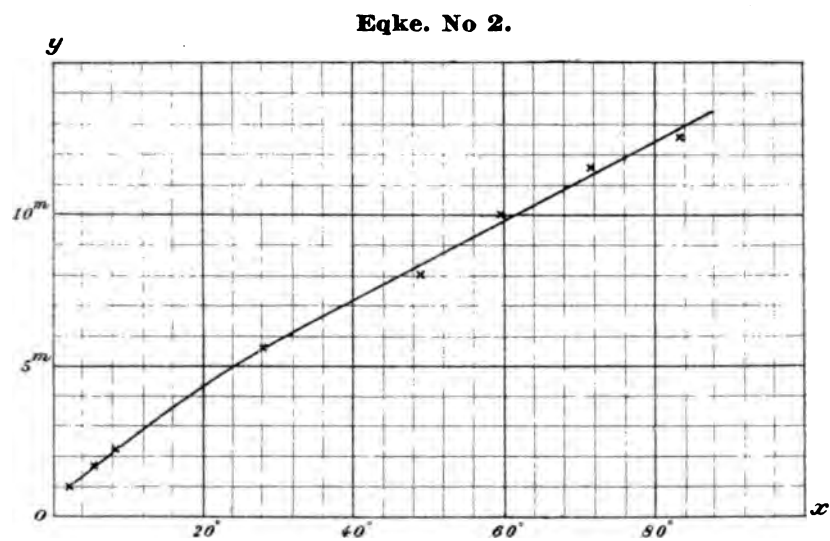
Miyako. ...	...37 ^m 52 ^s .	Slight.	{ Accompanied by verti- cal movement.
Ishinomaki. ..	38 8.	Do.	Gentle.
Akita. ...	38 16.	Do.	Do.
Kumagae. ..	38 54.	Slight (unfelt).	
Aomori. ...	38 54.	Do.	
Utsunomiya. ...	39 6.	Do.	
Tokyo. ...	39 42.	Do.	Gentle.
Fukushima. ...	38 23.	Do.	

Eqke. No. 24. May 27th 1904; 5h.

Mera. ...	40 ^m 0 ^s .	Weak (rather slight).	Houses shaken.
Yokosuka. ...	40 20.	Slight.	Windows rattled.
Tokyo. ...	41 49.	Do.	Gentle.
Yokohama. ...	32 26.	Slight (unfelt).	Do.
Kofu. ...	41 3.	Do.	Do.
Kumagae. ...	41 7.	Do.	
Ishinomaki. ...	41 50.	Do.	
Mito. ...	42 50.	Do.	



Fig. 1. Relation between arcual epicentral distance and time taken in transit by the 1st. preliminary tremor.



x =arcual epicentral distance.
 y =time taken in transit.

Kumamoto.	...41 ^m 42 ^s .	Slight (unfelt).	Duration long.
Yagi.	...42 52.	Do.	
Fukuoka...	...44 50.	Do.	

Eqke. No. 21. Dec. 3rd 1903; 17h.

Miyazaki.	...53 ^m 4 ^s .	Weak.	Houses shaken.
Kagoshima.	...52 45.	Weak (slight).	Do.
Oshima.	...52 40.	Slight (unfelt).	Gentle.
Kumamoto.	...53 40.	Do.	
Oita.	...52 45.	Slight.	

Eqke. No. 22. March 18th 1904; 22h.

Nemuro.	...24 ^m 32 ^s .	Weak.	{ Liquid in vessels over- flowed.
Akita.	...44 52.	Do.	Duration long.
Aomori.	...45 1.	Do.	Windows rattled.
Kushiro.	...49 40.	Do.	Clocks stopped.
Tokachi.	...54 12.	Do.	Houses shaken.
Abashiri.	...44 40.	Weak (rather slight).	{ Accompanied by earth- quake sound.
Ishinomaki.	...57 31(?)	Do.	
Shana.	...44 50.	Slight.	Gentle.
Kumagae.	...45 12.	Do.	Duration long.
Tokyo.	...46 15.	Do.	Gentle.
Nagano.	...46 40.	Slight (unfelt).	Duration long.
Iida.	...46 53.	Do.	Gentle.
Maebashi.	...47 31.	Do.	
Matsumoto.	...47 48.	Do.	Gentle.
Miyako.	...43 56.	Slight.	{ Accompanied by earth- quake sound.
Hakodate.	...45 6.	Do.	
Mito.	...45 0.	Do.	

$10^h 42^m 15^s$

$10^h 42^m 55^s$

$10^h 43^m 21^s$

$10^h 42^m 45^s$

$10^h 43^m 17^s$

$10^h 43^m 43^s$

1000

1000

1000

1000

$10^h 42^m 15^s$

$10^h 42^m 58^s$

$10^h 43^m 21^s$

$10^h 42^m 45^s$

$10^h 43^m 17^s$

$10^h 43^m 43^s$



**A Tide Rectifier,
or
An Instrument for eliminating the tidal
components from Tide-gauge Diagrams.**

By

T. Terada, *Rigakushi*.

With Plates XXVII–XXVIII.

The *rectifier*, whose object is to eliminate the principal tidal components of oscillations from tide gauge diagrams, may be of some interest in connection with the study of the oscillations of sea water, which is, under the direction of Prof. H. Nagaoka, being carried on by the Imperial Earthquake Investigation Committee. The details of the instrument are given in Pl. XXVII.

Each of the diagrams to be rectified, which were obtained by a portable mercury tide-gauge constructed after Mr. Nakamura's design¹⁾, consists of minor waves of periods $\frac{1}{2}$ –2 cm. in length, superposed on the tide waves of period over 20 cm. To effect the elimination of the larger waves from such a curve, the conditions to be fulfilled by the instrument are as follows:—

1) While a point, say *B* (fig. 1), traces a simple harmonic curve, another point, say *A*, describes a straight line.

2) The deviation of the tracer *B* from simple harmonic curve is faithfully reproduced on the straight line described by *A*.

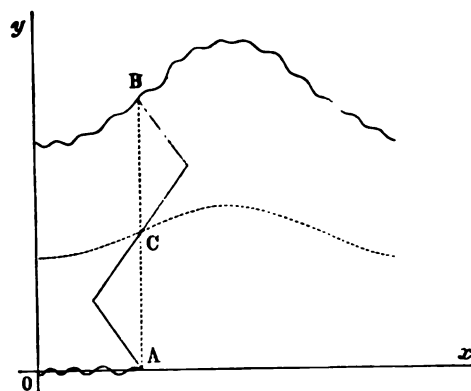
1) S. Nakamura. On a portable mercurial tide-gauge. Tokyo Sugaku-Butsu. G. K. Gaiyo (Reports of the meetings of the Tokyo Physics-Mathematical Society) Vol. I, No. 15, 1902.

3) The instrument must be adjustable to curves of different periods and amplitudes.

Simplicity of the construction as well as the operation is also desirable.

To fulfil the above conditions, pantographic joints (Pl. XXVII. JJJ) are made use of. The central pivot (C) is fixed to a slide (S) which is put in an oscillating motion of simple harmonic type in the direction of ACB with half the amplitude of that of the curve to be rectified, while the system moves in a direction perpendicular to ACB . Referring to Fig.

Fig. 1.



1, if A, C, B are the joints, we have always

$$AC = BC.$$

If the ordinate of the tidal curve be represented by y , we may put

$$y = a + b \sin nx + \sum_{m=1}^{\infty} b_m \sin n_m x.$$

Now, let C describe a curve

$$y' = \frac{a}{2} + \frac{b}{2} \sin nx$$

If the path of A be represented by y'' ,

$$y - y' = y' - y''$$

$$\therefore y'' = 2y' - y$$

$$= - \sum_{m=1}^{\infty} b_m \sin n_m x$$

The negative sign shows that the minor waves are reproduced. If the minor oscillations were to be reproduced in a magnified or reduced amplitude, the ratio of the arms of the joints is to be changed accordingly. In this case

$$k(y - y') = y' - y''$$

$\therefore$

$$(k+1)y' = ky + y''$$

$$y = a + b \sin nx + \sum_{m=1}^{\infty} b_m \sin n_m x$$

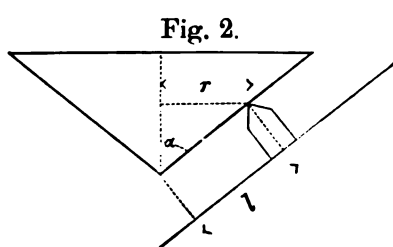
$$y'' = -k \sum_1^{\infty} b_m \sin n_m x$$

$$\therefore y' = \frac{ka}{k+1} + \frac{kb}{k+1} \sin nx$$

i. e. to magnify by k times, the amplitude of C must be adjusted to $\frac{k}{k+1}$ times that of the curve to be rectified.

The simple harmonic motion of the slide (S) is actuated by a peg (P), which slides smoothly in a groove (G), cut in the slide perpendicular to ACB , and fixed to a proper point of the crank (K) rotating with the conical wheel, (W) when the wheel rolls on the rail (R_1). The motion of the tracer (B) and the pen (A) is guided by the rails (LL). The whole frame-work rests and rolls on two rails (R_1) and (R_2). The latter is run over by a rectangular groove upon which fit two rollers attached to the frame. The former (R_1) has a sharp edge on which the conical wheel rolls. The rail rests on an inclined plane, parallel to the generating line of the cone passing through the point of contact with the edge, so that if the rail is shifted parallel to itself, the plane of rotation of the wheel remains unaltered. The edge is stretched over with a thin sheet of cautchouc to prevent the dead slip.

The period, *i. e.* the distance swept over by the instrument in one revolution of the wheel, is determined by the point of contact of the one with the rail (R_1). Referring to Fig. 2,



$$l = r \operatorname{cosec} \alpha$$

The period $T = 2\pi r$

$$\therefore l = \frac{T}{2\pi} \operatorname{cosec} \alpha$$

A table for the values of l for different values of T , may facilitate the adjustment.

The adjustment for the amplitude, may be performed by shifting the peg (P) to a proper distance from the axis of the crank, by means of a nut fixed to the peg, and a screw. The position of (P) may be

read on a scale on the side of the crank. When these adjustment have been made, the instrument is ready for the operation.

Since the tidal curve is by no means simple harmonic, the elimination of a single component is not generally sufficient for the perfect rectification of a sheet of mareogram which contains maxima or minima of different amplitudes. Though this may be achieved by successive eliminations, it seems more plausible for the practical purpose to proceed as follows. The curve is rectified, as it were, piece by piece, *i.e.* we divide the curve into a number of portions each of which may approximately be regarded as simple harmonic, rectify them successively and arrange the rectified pieces into a continuous line. Fig. 1, Pl. II rectified in this way gives Fig. 2.¹⁾

The following are some of the other applications of the instrument:--

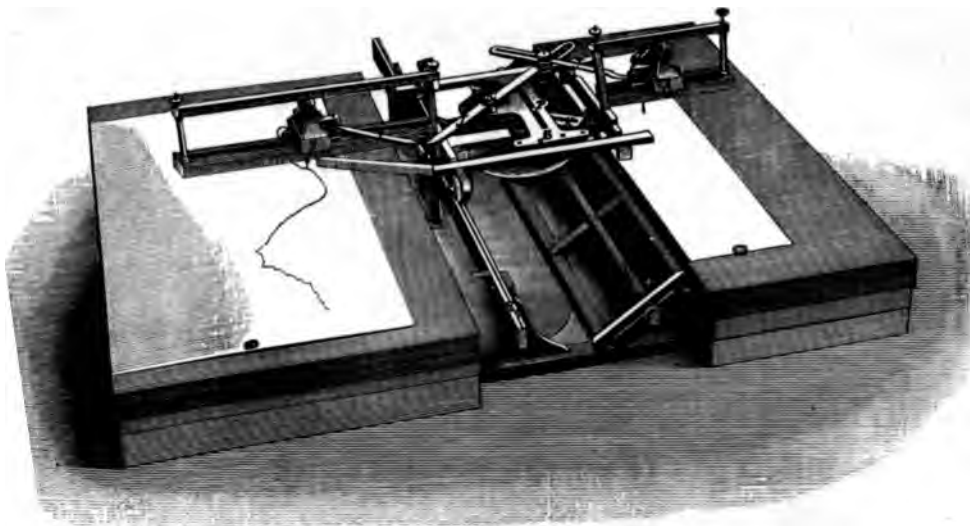
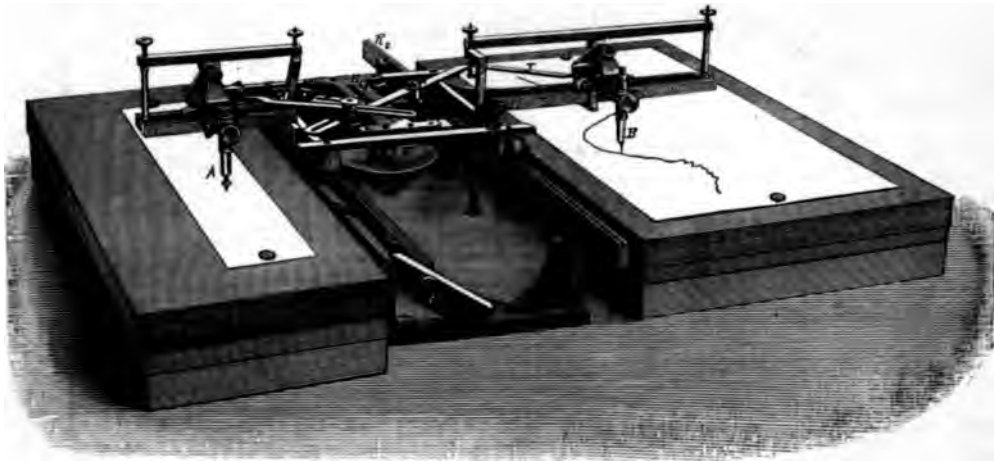
1) If the tracer and the pen are interchanged and the former is drawn along a straight ruler, the latter describes a simple harmonic curve of desired size, provided suitable adjustments be made.

2) If the simple harmonic curve thus obtained be brought under the tracer and the phase of the crank as well as the position of the peg and the rail be properly adjusted, we may obtain a curve which is composed of two simple harmonic curves of desired size and phase difference. By successive operations, any desired numbers of simple harmonic curve may be composed, as long as the amplitude of the resultant curve does not exceed the limit as is naturally determined by the length of the rails (LL).

3) The instrument seems to be particularly adapted for rectifying diagrams of alternate currents such as those given by Dudell's oscillograph.

1) Here, the inverted curve is inverted once more by means of a tracing paper.

Pl. XXVII.



Note on the Horizontal Pendulum Observations at Osaka.

By

F. Omori, *Rigakushi, Rigakuhakushi,*
Member of the Imperial Earthquake Investigation Committee.

With Plate XXIX.

1. Introduction.

The continuous earthquake observation at the Osaka Meteorological Observatory was commenced in 1901 with an Omori Horizontal Pendulum¹⁾ of multiplication 6 and of free period of vibration of 25 sec., set up so as to record the EW component motion, and 254 earthquakes have been there recorded in the course of 2 years 7 months between June 1901 and Dec. 1903. The following notes are based on the results of analysis of the diagrams of these earthquakes and of pulsatory oscillations given by Mr. N. Shimono, Director of the Observatory, in Nos. 1 and 2 of the "Osaka Chidō Kansoku Hōkoku" (Reports on the Horizontal Pendulum Observations of Earthquakes at Osaka).

2. Pulsatory Oscillations.

(a) *Frequency.* The following table gives the number of days, on which pulsatory oscillations occurred, in each of the months between June 1901 and December 1903, as well as the total monthly duration of storms of these movements in 1903.

1) The instrument was of simple construction, which is similar to that shown in Pl. III, the *Publications*, No. 5.

Year. Month.	1901.	1902.	1903.	Mean.	Total monthly duration (1903).
	Days.	Days.	Days.	Days.	Hours.
Jan.	—	9	17	13.0	288
Feb.	—	11	13	12.0	228
March.	—	8	12	10.0	192
April.	—	8	5	6.5	72
May.	—	8	8	8.0	108
June.	—	5	5	5.0	60
July.	—	3	6	4.5	108
Aug.	—	6	1	3.5	12
Sept.	2	4	2	2.7	24
Oct.	5	9	16	10.0	324
Nov.	5	8	9	7.3	108
Dec.	12	19	16	15.7	312
Sum.	—	98	110	104.	1836

From figs. 1 and 2, Pl. XXIX, which illustrate graphically the results contained in the above table, it will be seen that the frequency of pulsatory oscillations in the months April to September is much smaller than in October, December, January, February and March. The mean maximum and minimum monthly numbers of the days with pulsatory oscillations were respectively 15.7 and 2.7 which are in the ratio of about 6: 1.

(b) *Period.* In the 123 cases of pulsatory oscillation storms, observed during the 1 year 7 months between June 1901 and Dec. 1902, the average period of vibration varied between 3.1 and 6.9 sec, and had a general mean of 5.1 sec.; the number of cases, in which the average period was between 4.0 and 5.9 sec., being 114. Again, in the 113 cases of pulsatory oscillation storms in the year 1903, the average period, with a single exception of 2.4 sec., varied between 3.0 and 6.4 sec, and had the general mean of 4.9 sec.; the number of cases, in which the average period was between 4.0 and 5.9 sec., being 100.

Thus the mean period of vibration of pulsatory oscillations at

Osaka may be taken at about 5.0 sec., which is not much different from one of the fundamental vibration periods at Tokyo, namely, 4.4 sec.¹⁾; the other fundamental period of pulsatory oscillations at Tokyo being 8.0 sec. It is probable that a careful examination of the Osaka diagrams will also indicate the existence of pulsatory oscillations of about 8 sec. period, as is to be inferred from the presence of vibrations of such period in the preliminary tremors and the end portion of earthquakes observed at the same place. (See next §.) I may here note that pulsatory oscillations of about 8 sec. period have also been observed at Leipsic with Prof. Wiechert's astatic pendulum.²⁾ It may be that the predominating period or periods of pulsatory oscillations, which are characteristic to the different places of observation, are approximately constant all over the world.

3. *Periods of earthquake vibrations.*

The 254 earthquakes before mentioned are divided, according to origin, into the following nine groups:—

- Group I. Distant earthquakes. (46 earthquakes.)
- Group II. Earthquakes which originated off the eastern coast of Hokkaido. (6 earthquakes.)
- Group III. Earthquakes which originated off the north-eastern coast of the Main Island. (33 earthquakes.)
- Group IV. Earthquakes in the vicinity of Tokyo. (55 earthquakes.)
- Group V. Earthquakes in Central Japan. (11 earthquakes.)
- Group VI. Earthquakes in the Kinai Provinces. (27 earthquakes.)
- Group VII. Earthquakes in Kyushu. (15 earthquakes.)

1). F. Omori; Horizontal pendulum observations, etc. The *Publications*, No. 13.

2). Franz Ertzold: Bericht über die von Wiecherts astaticem Pendelseismometer in Leipzig vom 1. Januar bis 30. Juni 1903 registrierten Fernbeben und Pulsationen. Berichte der mathem. physichem Klasse der K. Sächs. Gesellschaft der Wissenschaften zu Leipzig, 1903.

Group VIII. Earthquakes in Formosa and off the Lyū-Kyū Islands. (15 earthquakes.)

Group IX. Local earthquakes, or those which originated in the immediate vicinity of Osaka. (36 earthquakes.)

As the Osaka instrument had a too great stability, there appeared very often proper pendulum oscillations in the principal part of earthquakes, consequently I take here only the preliminary tremors and the end portion, for which the average values of the different kinds of period are as follows, the figures within brackets indicating the number of cases from which the respective values of the periods have been deduced.

PERIODS OF VIBRATIONS AT OSAKA.
(EARTHQUAKES OF GROUPS I-IX.)

Group. Phase of eqke. motion.	I, II, VIII.	III, IV, VII.	V, VI.	IX.
1st Preliminary Tremor.	sec. 1.7 (4) 2.2 (3) 3.0 (20) 4.9 (25) 7.5 (6)	sec.	sec.	sec.
2nd Preliminary Tremor.	1.2 (1) 2.4 (2) 3.6 (15) 5.2 (20) 8.6 (8)			
1st and 2nd Preliminary Tremors taken together.		— — — 4.7 (13) 7.1 (3) 15.6 (4)	0.8 (8) 1.4 (14) 2.7 (1) — 5.6 (3)	— — 1.7 (3) 3.2 (7) — 4.9 (9)
End portion.	— — — 6.2 (20) 8.8 (7) 14.3 (7)	— — — 2.4 (14) — 6.0 (6) 8.7 (3) 15.8 (3)	1.4 (7) 2.0 (8) 4.2 (10) — — —	— — — 2.8 (4) 5.1 (7) — 8.1 (3)

In the above table, the periods most frequently occurring in each phase of the motion are printed in thick letters. The averages of the different periods taken from the preliminary tremors and end portion are as follows, the figures within the brackets having the same signification as before:—

0.84	sec.	(9)
1.5	„	(28)
2.7	„	(59)
3.8	„	(25)
5.3	„	(103)
8.2	„	(30)
15.0	„	(14)

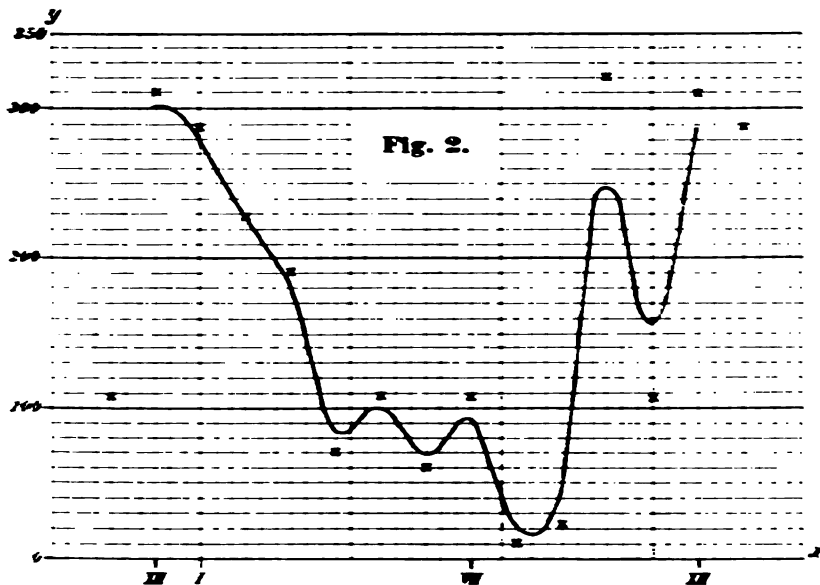
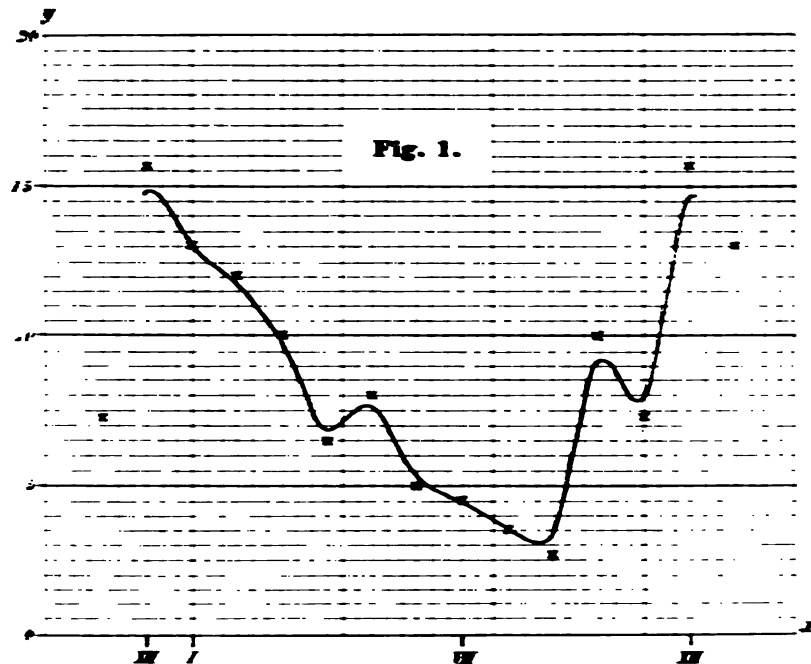
Of these 7 classes of periods, the first two characterize the macro-seismic movements at Osaka, the rest being of the nature of micro-seismic or insensible movements. It is to be noted that the period most frequently occurring, namely, that of 5.3 sec., is practically identical with the average period of pulsatory oscillations at Osaka. Periods of vibrations approximately equal to the 3rd, 5th, 6th, and 7th are found also in the earthquakes observed at Tokyo.

Tokyo. Aug., 1904.

1. The first part of the document is a list of names and dates, which appears to be a record of some kind. The names are written in a cursive script, and the dates are in a more formal, printed style. The list is organized into two columns, with names on the left and dates on the right.

2. The second part of the document is a single line of text, which appears to be a signature or a name. It is written in a cursive script, and is located at the bottom left of the page.

Annual Variation of the Frequency of Pulsatory Oscillations at Osaka.

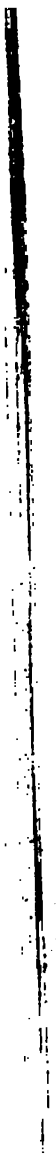


x = Month.

Fig. 1. y = Monthly number of days, on which Pulsatory oscillations took place.

x = Month.

Fig. 2. y = Monthly number of hours during which Pulsatory oscillations took place.



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RECENT SEISMOLOGICAL INVESTIGATIONS

IN

JAPAN.

BY

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Honorary Professor of the Imperial University of Tōkyō,

Member of the Imperial Earthquake Investigation Committee.



NOTE.

This paper was prepared with the purpose of being delivered as an address at the Congress of Arts and Science of the Louisiana Purchase Exposition at St. Louis and small number of copies was printed for private circulation. But I was prevented almost at the last moment by unavoidable circumstances from leaving Japan, and it has now been decided to publish it as one of the Publications of the E. I. C. in foreign languages.

There is one remark that I wish to make here in order to prevent any misconception that may possibly arise from statements in this paper. I have stated that we have, taking the whole of Japan, nearly 1400 earthquakes recorded yearly; in Tōkyō alone, there are about 50 sensible earthquakes in a year, that is, about once a week. Now it might be thought from this, that we in Tōkyō must be living in a state of constant feeling of insecurity, but this is of course far from being the case : of these 50, large number is very slight, so slight that they would not be noticed at all except by a special few ; I may say that only once or twice a year at most, do people in Tōkyō have occasion to feel even temporary and slight alarm, and yet Tōkyō is in the most disturbed region of Japan.

I have to express my warmest thanks to Prof. Omori who has most kindly assisted me in every way, from the first getting together of materials to the last correction of proofs, and also to Professors Tanakadate, Kotô and Nagaoka, of Science College, members of the E. I. C., for their valuable suggestions and criticism ; and to Dr. K. Nakamura, Director of the Central Meteorological Observatory, also a member of the E. I. C., for giving me informations on many points; likewise to Prof. Purvis of the Engineering College, who has looked over the paper and helped in seeing it through the press.

Aug. 31st, 1904.

D. Kikuchi.

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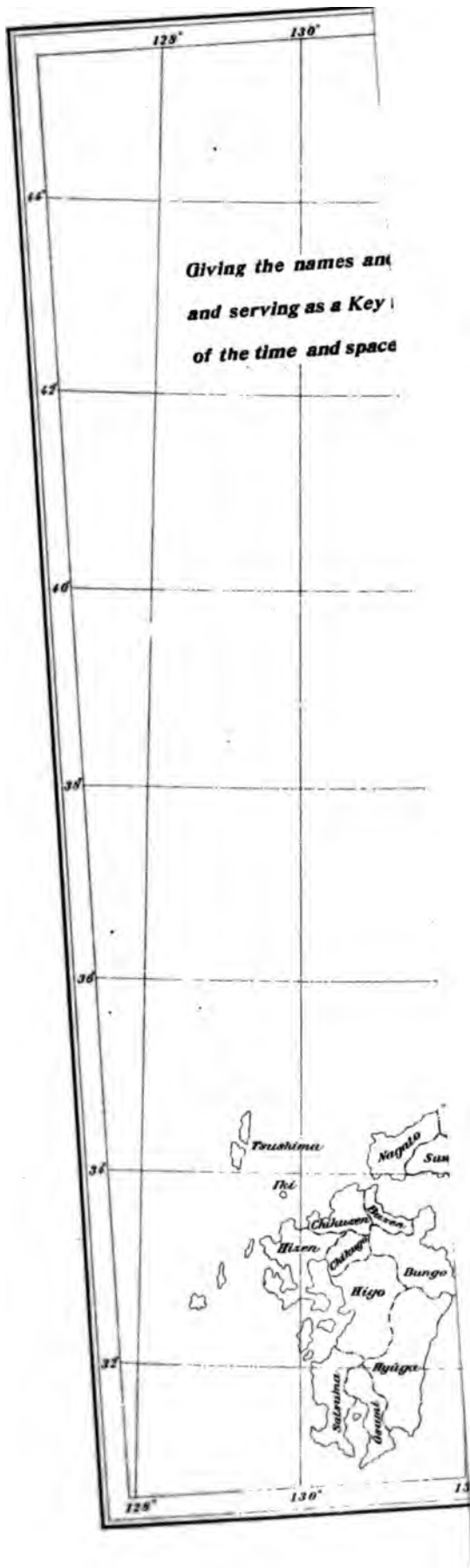
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RECENT SEISMOLOGICAL INVESTIGATIONS IN JAPAN

CHAPTER I. INTRODUCTORY.

1. Japan is preëminently a land of Earthquakes. The number of earthquakes in the whole of Japan in the year 1903 was 1349, which is by no means above the average. Since 1872, 15 earthquakes have occurred sufficiently severe to cause loss of life or serious damage to property: it may be added that this number would have to be considerably increased, if we included such shocks as would have caused damage in Europe or America, where buildings are much higher than in Japan without precautions being taken against earthquake shakings.

2. The earthquakes come with such suddenness, their effects are often so terrible, there is something so mysterious about them, that they have attracted the attention and excited the wonder and terror of our countrymen from the earliest times. The first mention of an earthquake in the authentic history of our country is in the reign of Emperor Inkyō. A. D. 416, when the district of Kawachi was very severely shaken. Since then up to the year 1867, over 2000 earthquakes are recorded in history, of which some were very severe, causing considerable damage and loss of life.¹⁾

3. In 1854 (the year of the conclusion of the first treaty with

1) A catalogue of these earthquakes in English is given in the Jour. Sc. Coll. (Journal of the College of Science, Tōkyō Imperial Univ.), Vol. XI, pp 315-435.

the United States), a gentleman in Tosa counted the number and measured the intensity of the after-shocks of the terrible earthquake of that year by observing oscillations of a swinging body. In 1855, an intelligent shopkeeper in Tōkyō is said to have noticed that some time before the great earthquake of that year, several nails previously attached to a loadstone in his shop dropped from it; a physician thereupon devised an instrument in which this supposed property of a magnet is utilized to give warning of a coming earthquake by ringing a bell.

It was quite natural, therefore, that when Western Science and scientific methods began to be introduced into Japan, they should be applied to the investigation of the seismic phenomena. Soon after the Restoration of 1868, the Government anxious to introduce Occidental civilization and knowledge into Japan invited Europeans and Americans to act as advisers to government departments, and instructors in the newly established schools and colleges, and it was mainly by these that the scientific study of earthquakes was first taken up. It would be a difficult and invidious task to try to give proper credit to each individual, but a special mention is due to Prof. Milne, who by his infectious enthusiasm and untiring energy has done more than any other to stimulate interest in, and to advance the systematic study of the phenomena. In Seismometry, the names of Prof. T. Gray and Prof. J. A. Ewing will stand forth most prominently. Among others to be mentioned are Rev. C. F. Verbeck, who made observations with pendulum and other devices as early as 1872; Dr. C. Wagener; Prof. W. S. Chaplin, who was the first to apply the horizontal pendulum, now so much employed in seismographs, to seismometry; Prof. C. D. West; and Prof. C. G. Knott. The founding of the Seismological Society of Japan in 1880 gave a great



impetus to the study of earthquakes; 16 volumes of its Transactions,¹⁾ the last issued in 1892, together with 4 volumes of the Seismological Journal of Japan, which may be regarded as a continuation of the same, contain some of the most valuable contributions to the advancement of Seismology.

4. In 1875, Palmieri's Seismometer²⁾ was set up in the Central Meteorological Observatory in Tōkyō, and its indications were reported in the papers. This instrument continued to be in use until 1883, when it was replaced by seismographs of the type usually known in Japan as Gray-Milne's. A modified and improved form of these seismographs, together with arrangements for indicating the time of the shock, is now in operation, not only at the Central Meteorological Observatory and the Seismological Institute of the Tōkyō Imperial University with its branch stations, but also at 71 local meteorological stations. [See Art. 45.]

5. It had come to be felt by the more advanced among us, not only that the study of earthquake phenomena was of great practical importance to us, but also that organised scientific investigation connected with seismology was a duty which Japan owed to the scientific world. On the practical side were considerations of houses built in foreign style, arches, bridges, chimneys, &c, new to Japan; these were designed and constructed without proper attention to the probable effects of the earthquake shocks peculiar to this country, shocks not occurring except very rarely, and therefore not being taken account of, in the countries from which these structures were introduced. On the other hand, perhaps no other

1) Referred to subsequently in this paper as *Trans. Seism. Soc.*

2) A description of this instrument is given in the *Encyclopaedia Britannica*, 9th edition, Vol. VII, Art. "Earthquake."

country in the world offered such an opportunity for making a scientific study of the phenomena.

Thus, in 1886, when the University of Tōkyō was partially reorganised, a chair of Seismology was established in the College of Science, and Mr. S. Sekiya was appointed first professor of Seismology; he had previously to this taken up the subject as his specialty at my suggestion and had been in charge of a small seismological laboratory in the University, under the superintendence (at first) of Mr. J. A. Ewing, Prof. of Mechanical Engineering and of Physics. The chair has been occupied, since the lamented death of Prof. Sekiya, by Prof. F. Omori (who also took up this specialty at my suggestion). The chair is unique in the world. The Seismological Institute attached to the chair was removed last April to a little more commodious building than it had hitherto occupied.

6. In October, 1891, took place the great Mino-Owari Earthquake, felt throughout the whole of Central and Southern Japan, in which over 7000 people were killed, over 17,000 injured, and nearly 20,000 buildings destroyed, besides bridges, arches and miles of railways, embankments, &c. This earthquake, one of the severest ever felt, certainly the severest since the Ansei Earthquakes of 1854 and 1855, caused, as may be imagined, the profoundest impression throughout the whole country; a representation¹⁾ to the government was proposed in Dec. 1891 in the House of Peers, then in its second session, by myself, supported by the principal members, and passed by a large majority, calling upon the government to take steps to establish a bureau or appoint a committee for studying earthquakes with a view to lessen their

1) See the E. I. C. Publ., No. 3.

disastrous effects. In accordance with this representation, a committee was organized by Imperial Ordinance dated June 25, 1892, entitled the *Shinsai Yobō Chōsakai*, literally a Committee for investigating the prevention of earthquake disasters, more usually known as the Earthquake Investigation Committee. The object of the Committee is twofold:—in the first place to investigate whether there are any means of predicting earthquakes; and in the second place to investigate what can be done to reduce the disastrous effects of earthquake shocks to a minimum, by the choice of proper structures, materials, position, &c. The Committee has from the first taken a most liberal view of its functions and while always holding the above mentioned twofold object in view, has not hesitated to undertake any investigations within its means likely to tend to the attainment of this object, even such as are but indirectly connected with it, and would not have been necessary, had other bodies or individuals been doing the work (as would be the case in Europe or America). Its first president was Dr., now Baron, H. Katō, then the President of the Tōkyō Imperial University, with myself as secretary: on Dr. Katō's retirement next year, I became president and held the post until 1901, when I was succeeded by Prof. Tatsuno; the latter retired in 1903 and was succeeded by the present president, Prof. B. Mano. Prof. Ōmori, who has always been the most active member of the Committee, has held the secretaryship since 1897. Its present members are 24 in number, all scientific men or engineers. Its annual appropriation has been between 12 and 14 thousand dollars. It has so far published 47 numbers of reports in Japanese, and 16 in foreign languages, mostly English. [I give as

an appendix a list of the contents of these reports, which will show what kind of work it has been doing.]¹⁾

7. As the recent seismological investigations in Japan are almost wholly the work of this Committee in conjunction with the Seismological Institute of the Tōkyō University, what I am going to say will practically be an account of that work and its results.

The work may for convenience be classified as follows:—

1) *Statistical*: consisting chiefly of collecting of records and reports of earthquakes and “*tsunamis*”²⁾, descriptions of the effects of the shocks, &c. From these data are deduced the distribution of earthquakes (*a*) in time, and (*b*) in space; their relation to the seasons, the phases of the moon, the times of the day, and the meteorological conditions; parts of the country most shaken, maritime or inland, &c.

2) *Instrumental*: consisting of observations with seismometers and seismographs; investigations into the construction of instruments, the invention of new, and improvement and modification of old; “the Seismic Triangulation,” &c. From these observations, are deduced the nature of the vibrations of earth particles, their amplitude and period, the velocity of earthquake waves, and so on. The observations of distant earthquakes also come under this head.

3) *Geological*: including reports of volcanic eruptions, dislocations, &c. Under this heading comes also the Vulcanological Survey, whose object is “to study the new and old volcanoes of

1) In the subsequent part of this paper, the Committee will be referred to as the E. I. C., its reports in Japanese as the E. I. C. Hō (its full Japanese title being Shinsai Yobō Chōsakai Hōkoku) and its publications in foreign languages as the E. I. C. Publ.

2) “*Tsunami*.” This is the Japanese name for those destructive sea waves, which frequently devastate the coast of Japan. They have often been designated “tidal waves” or “seismic sea waves,” but I have preferred to retain the original name.

our country as regards their internal structure, their rocks, their foundations and their modes of distribution,"¹⁾ so as to be able to get "an insight into the structure of the land;" and "to construct the geotectonic map, by means of which we could possibly know the condition underground, and the causes of the regional shaking and the local points of earthquakes."

4) *Physical*: consisting of investigations of such physical phenomena, as it seems reasonable to suppose *a priori* have some relation with seismic phenomena, with a view to ascertain whether such a relation does really exist, and if so, what is its nature. Among these are Earth Magnetism, Variation of Latitude, Gravity, Underground Temperature, Seiches, Elasticity of Rocks, &c. These investigations, by establishing a relation between earthquakes and some phenomena which we can observe continuously, might help us towards the ultimate object of the E. I. C., viz, the earthquake prediction.

5) *Practical*: this forms a special feature of the work of the E. I. C., being one of the two ultimate objects, for which the Committee was organized. It comprises investigations of earthquake-proof structures, best forms for chimneys, piers, columns, &c.; the strength of materials and combinations of materials, and so on. The Committee has also extended its work to the application of seismometrical instruments to the measurement of vibrations of the ground, and of vibrations of buildings and structures, due to causes other than earthquakes, such as passing of trains over bridges, hammering in factories, and the like, and to an examination of their effects. Evidently, this investigation must to a very

1) Prof. B. Kotō: The Scope of the Vulcanological Survey of Japan; the E. I. C. Publ., No. 3.

large extent depend upon the results of the work mentioned under the preceding heads.

CHAPTER II. STATISTICAL.

8. We have at present, besides the laboratory of the Seismological Institute of the Tōkyō Imp. Univ. and stations in direct telegraphic communication with it in Tōkyō and its suburbs, the Central Meteorological Observatory also in Tōkyō with full seismographic equipment, Kyōto Imp. Univ., 71 local meteorological stations provided with seismographs, and 1437 stations not provided with instruments, scattered throughout Japan. From all of these, reports of earthquakes observed or felt are sent to the Central Meteor. Obs. The 71 stations above-mentioned are in telegraphic communication with the nearest telegraph office and receive time daily direct from the Tōkyō Astronomical Observatory,—an arrangement initiated and maintained at the cost of the E. I. C.

9. The E. I. C. appointed Mr. Tayama to search for and examine the accounts of earthquakes recorded in history and in “the materials for history,” under the superintendence of Prof. Sekiya, and after his death, of Prof. Ōmori. The result of his work is given in the two volumes forming No. 46 of the reports of the Committee, and entitled “The Materials for the Earthquake History of Japan;” in it are collected extracts from nearly five hundred books, pamphlets, reports, diaries, &c. relating to over two thousand earthquakes between the years 416 and 1867. Some of these give very full account of the damage caused, of various occurrences supposed to have been premonitory, of the state of the popular feeling at such times, and so on, so that they will be valuable not merely to seismologists, but to historians, sociologists,

psychologists and others. This work owes much of its completeness to the courtesy of the Shiryō Hensan Gakari (Committee for the Compilation of Materials for the History of Japan) of the Tōkyō Imperial University, to whose collected materials Mr. Tayama was allowed free access at the request of the E. I. C.

10. The E. I. C. has sent its members and others to the scenes of very strong earthquakes, of which there was an unusually large number in the nineties, beginning with the great Mino-Owari earthquake (Oct. 28, 1891); notably those of Noto (Dec. 9, '92), Kagoshima (Sept. 7, '93), Eastern Hokkaidō or Yezo (March 22, '94), Tōkyō and vicinity (June 20, '94), Shōnai (Oct. 22, '94), Ugo and Rikuchū (Aug. 31, '96), Nagano (Jan. 17, '97), Sendai and Eastern Rikuzen (Feb. 20, '97), besides the destructive "tsunami" along the north eastern coast on June 15, '96, and in addition several volcanic eruptions, landslips, subterranean noises, &c. The Committee has even sent members to foreign countries or asked the Japanese consuls and others to report on similar phenomena, for instance the Indian Earthquake of June 12, 1897. The Reports presented will be found in several numbers of the E. I. C. Hō.

From the materials obtained in the above ways, many important conclusions have been arrived at, both of theoretical interest and of practical importance: some of these I proceed to state below.

(A) Time Distribution of Earthquakes.

11. The earth's crust is under continual stress, and when the strain thereby produced reaches a certain limit, the stress must be relieved, generally by some sudden (geotectonic) convulsions, thus

1. The first part of the document is a list of the names of the persons who have been appointed to the various offices of the city of New York.

10

causing earthquakes. Among the forces acting on the earth's crust, there are external ones like the atmospheric pressure, the attraction of the moon, &c., having different periods. Hence, we may reasonably expect to find some such periods in the earthquake frequency: we shall see how far the result of observations fulfils this expectation.

Destructive earthquakes.

12. *The total number of destructive earthquakes in Japan (Formosa excepted) during nearly 1500 years since 416 is 223. Confining our attention to the period of the Tokugawa Shōgunate and the Meiji era (i.e. from the commencement of the 17th century down to the present) during which the record of destructive earthquakes is, except for Hokkaidō and Lyū-Kyū, pretty perfect, we see that the mean interval between two successive destructive earthquakes has been, for the whole of Japan, about $2\frac{1}{2}$ years. The number of years in which one or more destructive earthquakes occurred is 78 in the interval of 303 years since the beginning of the 17th century, the maximum in one year being 3. In other words, 26 years in every 100 were visited by from one to three destructive earthquakes, the other 74 remaining free from such seismic disturbances.*

The distribution in time of the destructive earthquakes in Japan (Formosa, Lyū-Kyū, and Hokkaidō excepted) from the 8th century to the present is graphically shown in fig. 1, from which it will be seen that although shocks have sometimes happened singly or isolated, they have had a tendency to occur in groups. Thus 154 earthquakes since the beginning of the 14th century may be divided more or less definitely into 41 groups; the average

value of the intervals between the mean epochs of the successive groups being 13½ years.¹⁾

13. Annual Variation of the Frequency. If we take the destructive earthquakes by the months in which they occurred, we have the maximum of 32 in August, and minimum of 10 in January; if by the seasons, the maximum of 74 in summer, and the minimum of 48 in winter. These results are illustrated in figs. 2 and 4.²⁾

Comparing figs. 2 and 4 with figs. 3 and 5, it will be seen that the annual variation of the frequency of the destructive earthquakes is just the reverse of that of the ordinary small shocks. To explain this fact, it may be remarked that if an earthquake implies the removal of an unstable point in the earth's crust, and the consequent settling of the latter to a stable condition, the constant occurrence of small earthquakes is to be regarded as maintaining the region concerned in a comparatively safe condition, by preventing any abnormal accumulation of stress in the earth's crust: their non-occurrence or an unusually low seismic frequency may, on the other hand, cause an accumulation of stress in the earth's crust, thereby facilitating the occurrence of great or destructive seismic disturbances.³⁾

Earthquakes at Kyōto.

14. Kyōto was the capital of the Empire during the 1070

1) F. Omori: Notes on the E. I. C. Catalogue of Japanese Earthquakes. Jour. Sc. Coll., Vol. XI, pp. 411-413.

2) The curves are drawn, not always through representation points themselves, but by free hand through the positions of the arithmetical means of every two successive points. This method of curve drawing has been employed in the cases of other similar figures.

3) F. Omori: Notes on the E. I. C. Catalogue of Jap. Earthquakes. Jour. Sc. Coll., Vol. XI, pp. 403-408.

Fig. 2. Monthly Distribution of 216 Destructive Earthquakes in Japan.

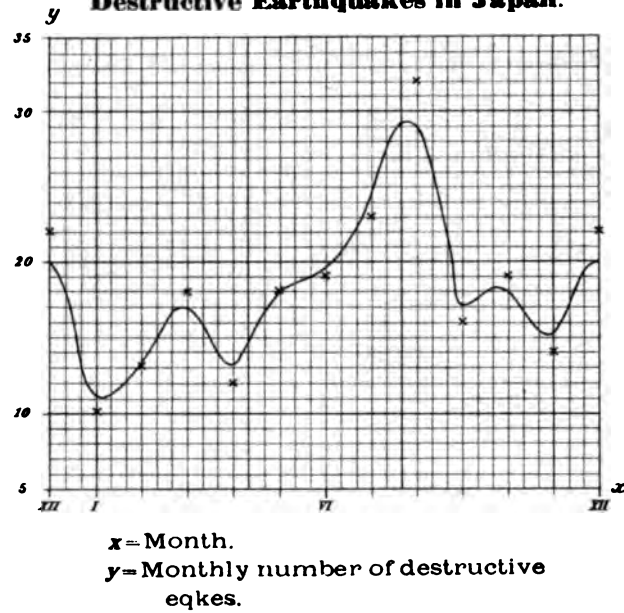


Fig. 3. Monthly Distribution of Ordinary Earthquakes in Japan.

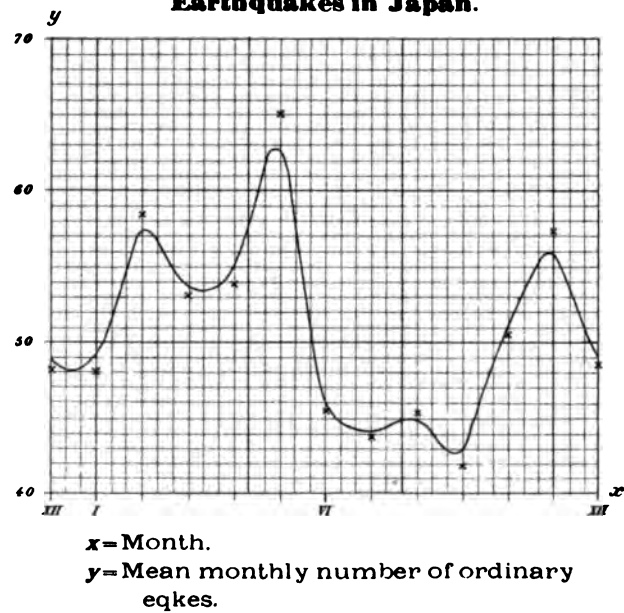




**Fig. 4. Seasonal Distribution of 216
Destructive Earthquakes in Japan.**

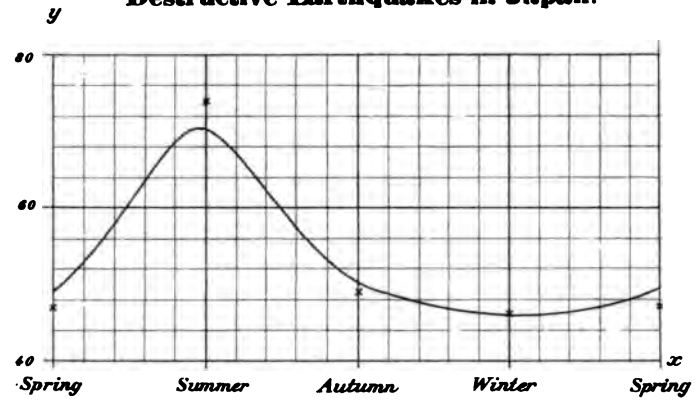
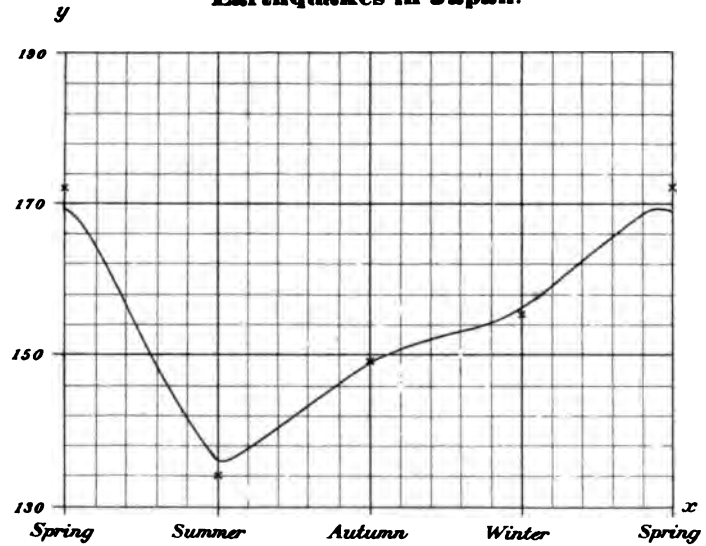


**Fig. 5. Seasonal Distribution of Ordinary
Earthquakes in Japan.**



years between 797 and 1867. Being the centre of literary culture during this period, earthquakes in this city have been very carefully recorded, and a unique instance is thus furnished in which a complete earthquake record at one place has extended continuously over a thousand years. Of the 1318 earthquakes at Kyōto, 34 were destructive, 194 "strong," and the remaining 1090 "slight" [see Art. 50].

The total number of destructive and strong earthquakes, which happened in Kyōto between the 9th century and the present time is 228, with time distribution as shown in fig. 6; this figure indicates a well pronounced maximum from the middle of the 14th to the middle of the 15th century, and then a steady decrease to a minimum in the first half of the 19th century. The seismic activity at Kyōto seems at present to be on its way to another maximum.¹⁾

The variation of the yearly activity of earthquakes in Kyōto for the two most disturbed epochs, namely, the 9th century, and the interval between 1340 and 1609 shows a series of fluctuations, whose average period is about $6\frac{1}{2}$ years.²⁾

Ordinary Earthquakes.

13. Systematic earthquake observation throughout the Empire was first organized in 1885. The total number of earthquakes observed during the 19 years between 1885 and 1903 was 27,485, which gives a yearly average of 1447 shocks, or a daily

1) See also Professor Milne's "Note on the great Earthquakes in Japan," Trans. Seis. Soc., Vol. III.

2) F. Omori: Notes on the E. I. C. Catalogue of Jap. Earthquakes; J. Sc. Coll., Vol. XI. pp. 418—434.

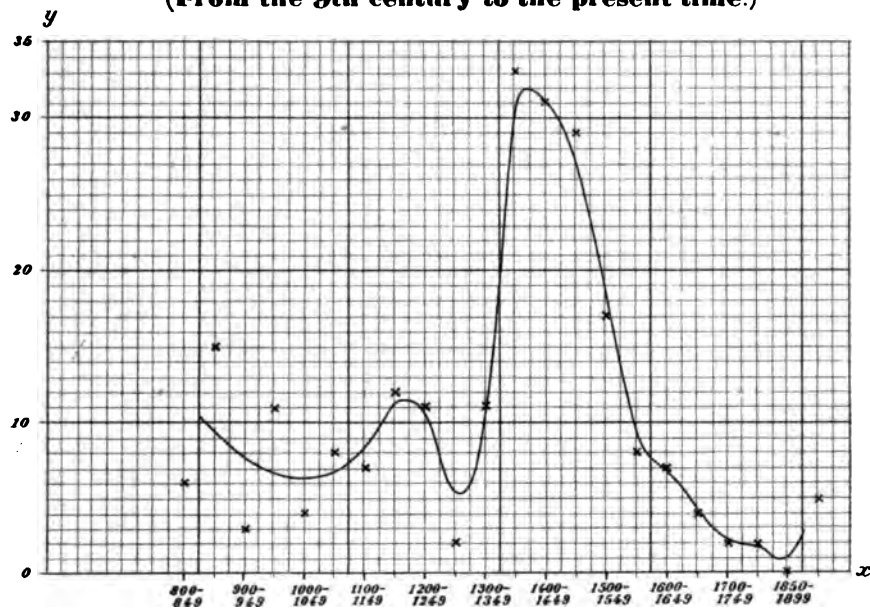
average of 4. The maximum earthquake number of 2729 occurred in 1894 and the minimum of 472 in 1886.

16. *Annual Variation of the Frequency.* There has been an enormous increase in the earthquake number since 1891: this is due to the occurrence of the Mino-Owari earthquake in Oct., 1891, and several very strong earthquakes in the subsequent years, each of these disturbances being followed by numerous after-shocks. The mean state of the seismic activity for the whole of Japan in ordinary years or those free from destructive earthquakes and their after-shocks is approximately as follows [see figs. 3 and 5 opposite p. 12]:—(1) The greatest monthly number of 65·3 occurred in May, and the smallest numbers, varying between 41·7 and 45·4, in June, July, August and September. (2) The maximum seasonal number of 172 occurred in Spring, and the minimum of 134 in Summer [cf. Art. 13.]

17. *Earthquakes in Tōkyō.* The earthquake observation in Tōkyō, in which instruments were used from the beginning, furnishes us with invaluable materials for questions connected with the annual and diurnal variations, as the records are not affected by any circumstances which may render the accuracy of the observation non-uniform in the different parts of the year or the day.

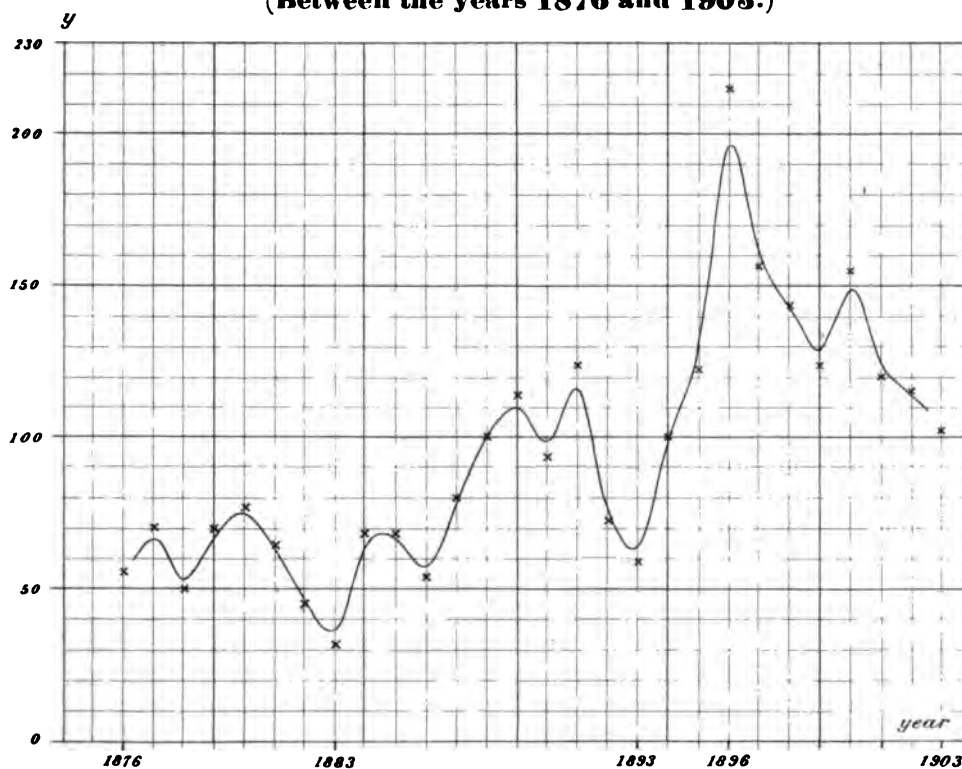
As stated in Art. 4, the earthquake observation in Tōkyō dates from the 8th year of Meiji (1875) and has now been continued for more than 28 complete years; the total number of earthquakes recorded up to the end of 1903 being 2657. The mean yearly number is 95, of which about 50 are sensible shocks. The secular variation of seismic frequency in Tōkyō is illustrated in fig. 7; the absolute minimum and maximum in the interval under consideration having occurred in 1883 and 1896 respectively. The general course of the curve seems to indicate a period of long

Fig. 6. Secular Variation of Seismic Frequency in Kyōto.
(From the 9th century to the present time.)



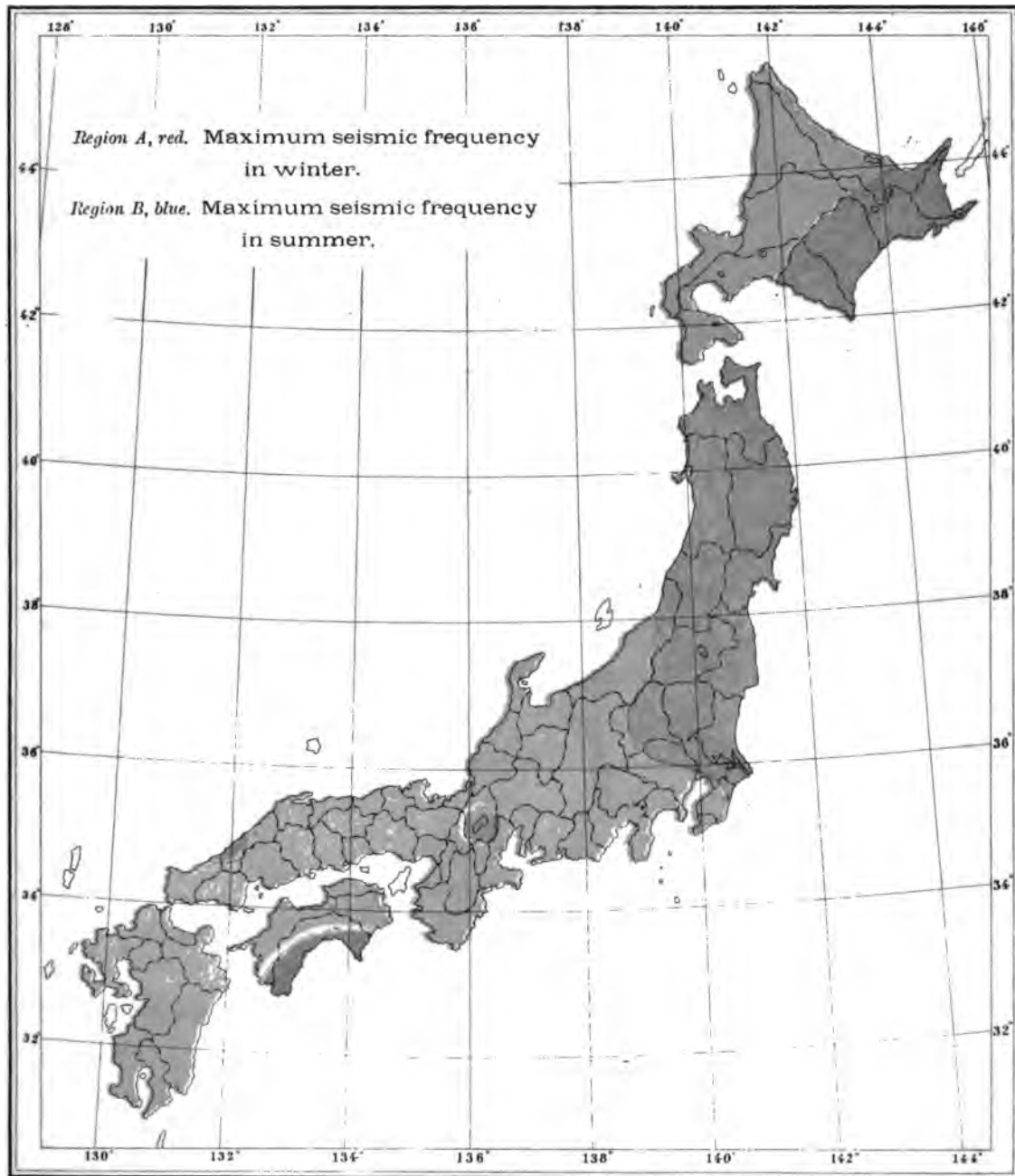
x = Time interval of 50 years.
 y = Total seismic activity during 50 years denoted by x .

Fig. 7. Variation of Seismic Frequency in Tōkyō.
(Between the years 1876 and 1903.)



y = Yearly number of earthquakes in Tōkyō.

**Fig. 8. Relation of Annual Seismic Variation
and Geographical Position.**



duration, the frequency decreasing on the whole from 1896 to the present time. It is hereby to be noted that the severest earthquake in Tōkyō in recent years [Art. 66] took place in 1894, the year 1893 being one in which the frequency was a minimum. The two next severest shocks took place in 1884 and 1887, and each was preceded by a year of minimum seismic frequency.¹⁾

18. *Relation of Annual Seismic Variation to Geographical Position.* What has been said in Art. 16 relates to the annual variation of the seismic frequency in Japan as a whole. The time distribution of earthquakes, however, is not necessarily the same for the different parts of Japan; in fact they may, according to the character of the annual seismic variation, be divided into two nearly opposite groups *A* and *B*, as follows:—At stations belonging to the group *A*, the seasonal maximum is mostly in spring and minimum mostly in summer or autumn; while at stations belonging to the group *B*, seasonal maximum is in summer, and minimum in winter or autumn. The dependence of the annual seismic variation on the geographical position may be seen from fig. 8, in which the regions belonging to the group *A* are coloured red and those belonging to the group *B* are coloured blue. It will be seen that the regions belonging to the two groups are separated into definite areas. Thus the *B* group region includes the whole north-eastern part of Japan, that is to say, the eastern half of Hokkaidō, the San-Riku provinces, the Ryō-U provinces, Iwaki, Iwashiro, Hitachi, Shimotsuke, the northern part of Echigo, the greater portion of Kōtsuke, the northern part of Musashi and the greater portion of Shimōsa. The vicinity of Hikone (bordering on Lake Biwa) and of Hamada, and the southern part of the Island of Shikoku also

1) F. Omori: Notes on the E. I. C. Catalogue of Japanese Earthquakes; J. Sc. Coll., Vol. XI., pp. 435–437.

belong to the *B* group region. The *A* group region includes the western half of Hokkaidō and the whole of Japan to the west of Echigo, Musashi and the Awa-Kazusa Peninsula, with the exception of a few isolated portions, which belong to the *B* Group region, as already mentioned.¹⁾

With regard to this peculiar geographical relation of the annual seismic variation, Prof. Omori remarks that on the whole, the earthquakes disturbing the *A* group region have inland origin, while those of the *B* group region have their origin mostly under the Pacific: a possible explanation is therefore to be found partly in the fact that the barometric pressure is at a minimum in summer and a maximum in winter; this pressure is the principal factor in the annual variation of the seismic frequency on land; on the other hand, Prof. Omori has observed that the level of sea water is higher in summer than in winter, so that the variation of the pressure on the ocean bottom is the reverse of what it is on land.

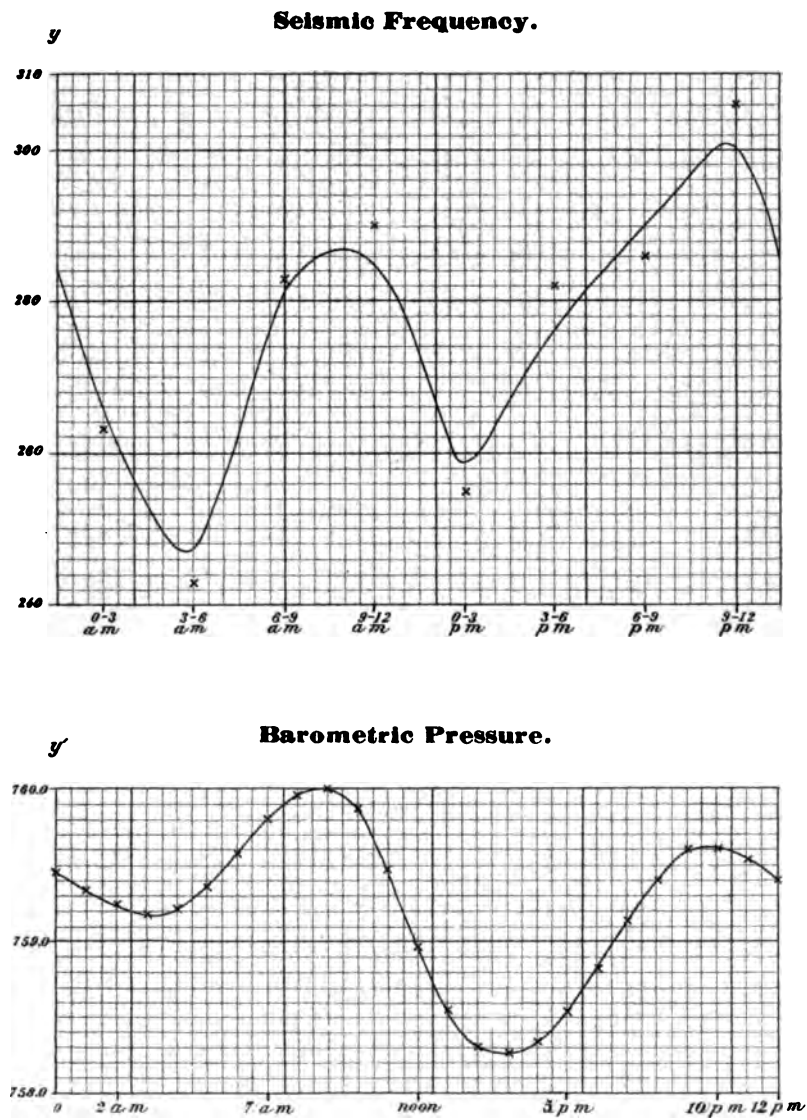
19. Diurnal Variation. The diurnal seismic period is clearly shown by the after-shocks of great earthquakes. In the case of the Mino-Owari earthquake of 1891, these shocks were very numerous, the successive hourly (or a-few-hourly) earthquake numbers, registered instrumentally at Gifu and Nagoya, indicating well-defined diurnal fluctuations.²⁾ The cause of the diurnal seismic variation seems to be the changes of the atmospheric pressure.

As an example, let us consider the diurnal variation in Tōkyō. Fig. 9 shows 3 hourly distribution of 2208 earthquakes instrumentally observed during the 24 years between 1876 and 1899; the

1) F. Omori: Annual and Diurnal variation of Seismic Frequency in Japan; E. I. C. Publ., No. 8, pp. 5-52, or E. I. C. Hō, No. 30, pp. 34-78.

2) F. Omori: On the After-shocks of Earthquakes; Jour. Sc. Coll., Vol. VII.

Fig. 9. Diurnal Variations of Seismic Frequency and Barometric Pressure in Tōkyō.



y =3-hourly number of earthquakes.
 y' =Mean barometric height in mm

curve indicates two maxima and two minima, while the curve of the barometric pressure indicates also two maxima and two minima. The forms of the two curves are very similar and nearly parallel to one another, the maxima and minima occurring at almost the same hours for both.

The diurnal variation for the whole of Japan shows approximately the same result. As, however, we may expect for some places to find the harmonics, or 12, 8, 6,...hours periods in the diurnal seismic variation, and as one or other of these various periods may predominate at each place, we may suppose the diurnal variation of seismic frequency to be a good deal different for different stations. An examination of the diurnal variation for different localities shows that they may be divided into four different groups according to the predominance in the diurnal fluctuation of 12, 8, 6, or 4 hours period.¹⁾

20. The study of the after-shocks of recent destructive earthquakes in Japan has indicated the existence, beside the annual and diurnal periods, of four others whose lengths were respectively $4\frac{1}{2}$ days, 12 days, 33 days, and about 3 months.

Prof. Omori has also shown that, with regard to the relation between the atmospheric pressure and seismic frequency other than the annual and diurnal variations, the seismic frequency may be accompanied by a maximum, minimum, or increasing or decreasing atmospheric pressure, according to the origin and cause of the earthquakes.²⁾

21. *Lunar Day Distribution of Earthquakes.* Fig. 10

1) F. Omori: Annual and Diurnal Variations of Seismic Frequency in Japan; E. I. C. Publ. No. 8, pp. 53-94, or E. I. C. Hō, No. 30, pp. 78-116.

2) F. Omori: Note on the Relation between earthquake Frequency and the atmospheric Pressure; Tōkyō Sūgaku Butsurigakkwai Kiji Gwaiyō (Proceedings of the Tōkyō Mathematical and Physical Society, referred to subsequently as Su. Buts. K. G.), Vol. II, No. 8.

shows the distributions in the lunar day of 1270 earthquakes at Nagoya, 799 earthquakes at Nemuro, and 1462 earthquakes at Tōkyō, respectively; the lunar day, counted from 0 to 24 hours, being the time interval between the two successive meridian transits at Tōkyō. The observations at Nagoya and Nemuro are respectively those of the after-shocks of the great Mino-Owari earthquake of 1891, and of the Hokkaidō earthquake of 1894; while the Tōkyō observations relate to ordinary shocks. Again, the earthquakes at Nagoya were almost entirely of inland, and those at Nemuro of submarine origin, and those at Tōkyō of mixed origin. Notwithstanding these differences in the origin, the curves of the lunar-day variation are nearly identical in character, each showing two maxima which occur respectively near or at the moon's upper and lower culminations.¹⁾

According to Dr. K. Honda, this dependence of the seismic frequency on the position of the moon is due probably not to the direct lunar attraction but to the tidal movement of the sea water which follows the motion of the moon.²⁾

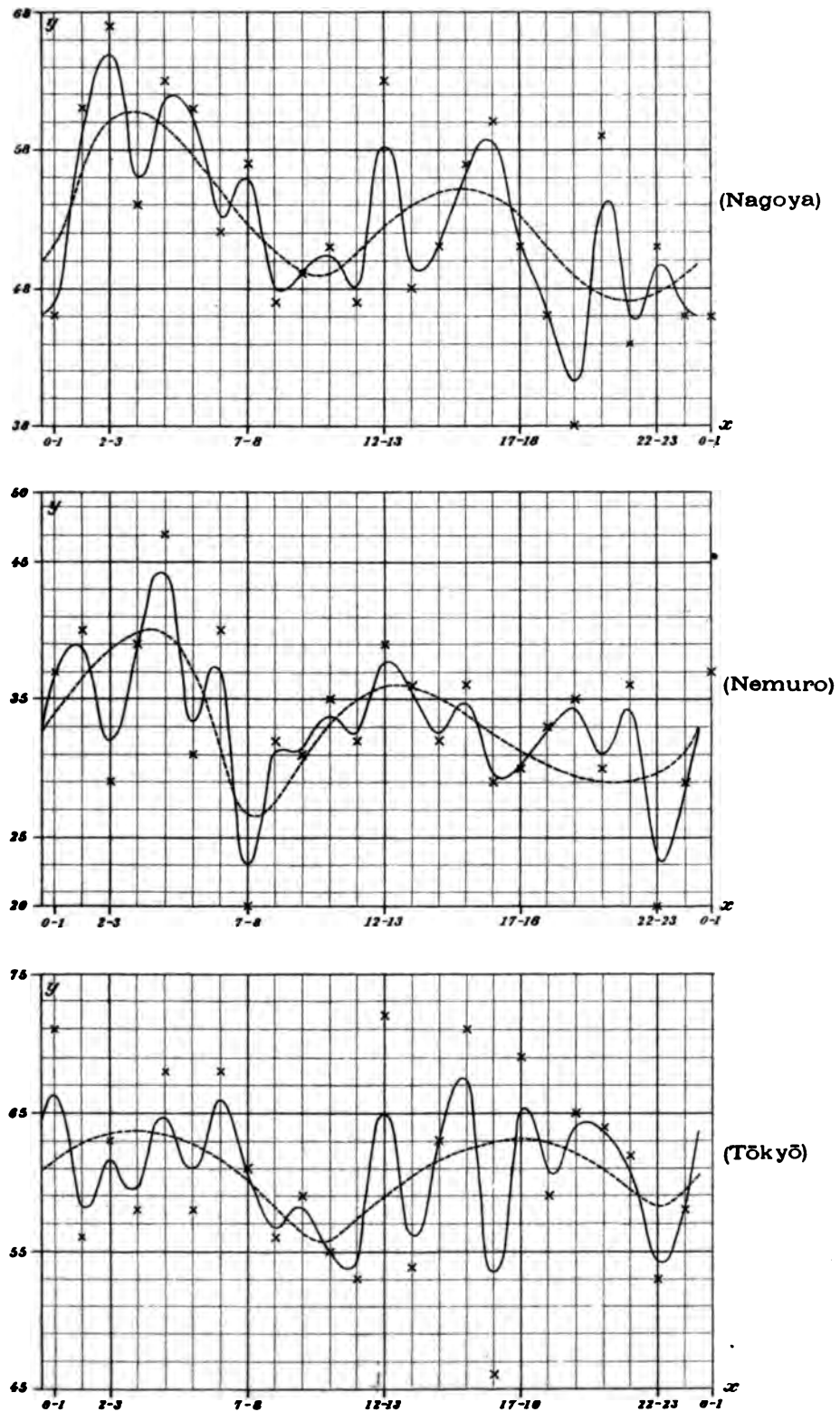
22. *Synodic-monthly Variation of Earthquakes.*³⁾ Distributing in the 30 synodic days the 1898 Japan historical earthquakes, the seismic frequency is found to be at a maximum not only at the times of the conjunction and opposition of the sun and moon, but also at the times of quadrature. This is also found to be nearly the case, from recent observations at different Meteorological stations, with earthquakes of submarine origin. On

1) F. Omori: Note on the Relation between the Seismic Frequency and the Position of the Moon; E. I. C. Hō No. 32.

2) K. Honda: Daily periodic Change of the Level in the Artesian wells in Yokohama and Okubo; Su. Buts. K. G., Vol. II, No. 9.

3) A. Imamura: Synodic-monthly Variation of Seismic Frequency in Japan; Su. Buts. K. G., Vol. II, No. 8.

Fig. 10. Lunar-daily Distribution of Earthquakes.



x = Lunar hour.
 y = Hourly number of earthquakes.



the other hand, those localities, which are shaken by earthquakes of inland origin are characterized by two maximum seismic frequencies at the days of the conjunction and opposition of the sun and moon. Finally of the 90 destructive shocks in Japan which occurred near the sea-coast, 29 occurred between 22nd and 26th days, 21 between 5th and 9th, 13 between the 14th and 18th, and 10 between the 28th and 2nd. The following may be regarded as an explanation for the existence of a pair of maximum frequency at the times of quadrature:—The barometric pressure which reaches its maximum in its diurnal variation at 9h and 22h, interferes with the tidal force, helping the latter when high water occurs at these hours, and cancelling it when low water takes place then.

After-shocks of Earthquakes.

23. A great earthquake is almost invariably followed by weaker ones, and when it is violent and destructive, the number of minor shocks following it may amount to hundreds or even thousands and continue for several months or several years. Complete instrumental records of these secondary shakings or *after-shocks* were first obtained in the cases of the Mino-Owari earthquake of 1891 and other great disturbances of recent years in Japan.

The occurrence of after-shocks is quite natural and necessary for the settling down into stable equilibrium of the disturbed tract at the origin of disturbance; each of these shocks removing an unstable or weak point underneath. Further, as a very great shock would remove a correspondingly great underground instability, it is probable that such a shock would not, for a long time,

be followed by another of a magnitude comparable to its own, in the same or a neighbouring district. When, however, the initial shock is not very great, it may be followed by another like it, but, even in this case, the position of the origin of the second shock would usually be quite distinct from that of the first.¹⁾

The frequency of after-shocks at a given distance from the origin is different for different earthquakes and depends mainly on the magnitude of the initial earthquake. Thus, in the case of the Mino-Owari earthquake, more than 4000 shocks were recorded at Gifu in the course of the six years following the initial disturbance.

24. *Time Variation of the Frequency of After-shocks.*

The mean time variation of after-shocks follows a very simple law and may be represented by means of a rectangular hyperbola. [See fig. 11.] Thus, denoting by x the time and by y the corresponding frequency of after-shocks, we have the following relation: $y = \frac{k}{h+x}$, in which k and h are constants to be properly determined for each case.

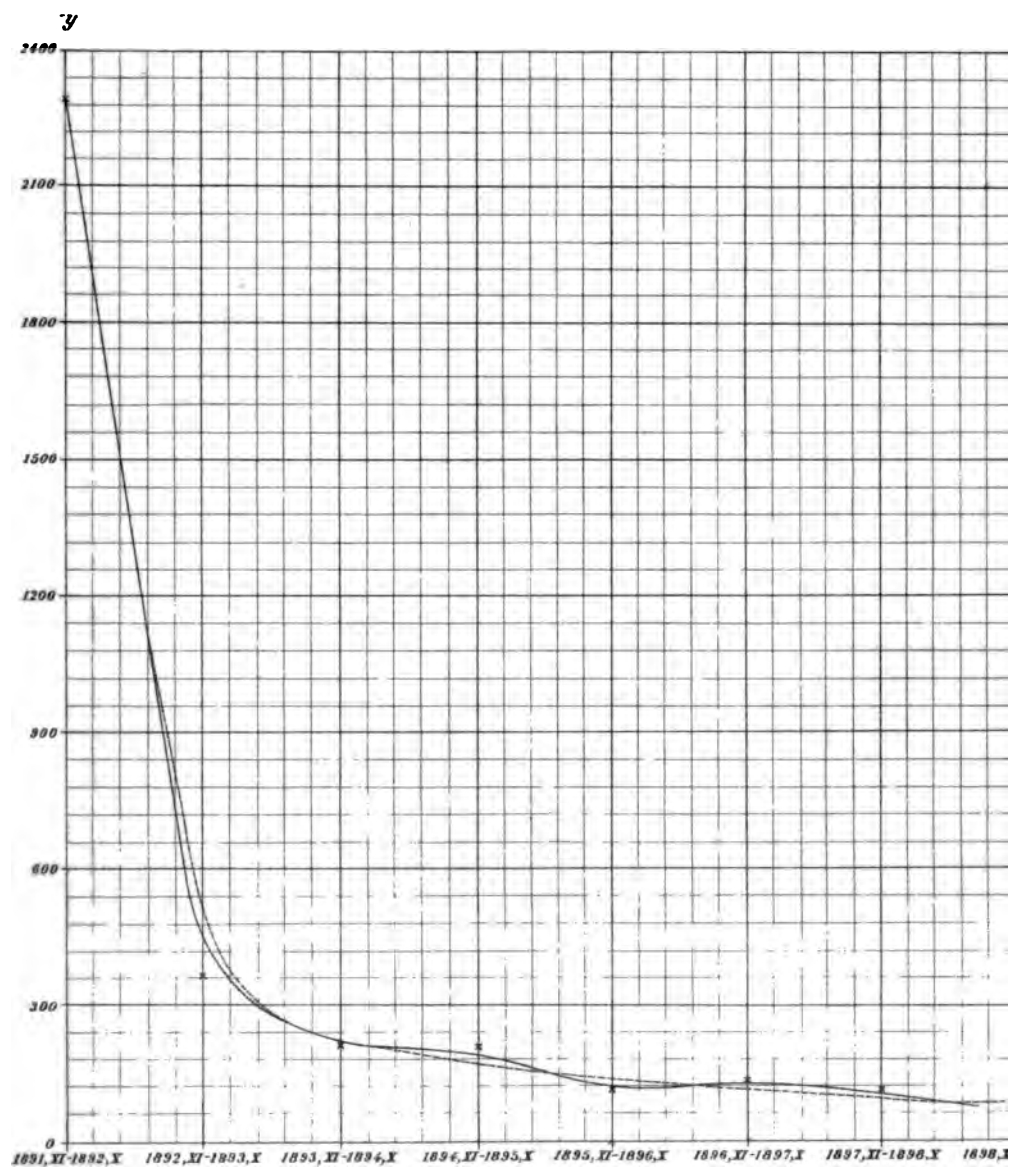
The Mino-Owari earthquake took place on Oct. 28th, 1891, at 6h 37m a.m. (Gifu). Taking the semi-daily earthquake numbers observed instrumentally at the Gifu meteorological station during the five days between Oct. 29th and Nov. 2nd, 1891, and calculating by the method of Least Squares, the above equation assumes the form $y = \frac{440.7}{x+2.314}$, in which y denotes the number of earthquakes observed at Gifu during the 12 hours denoted by x ; the time origin, expressed by $x=0$, corresponding to the first half of Oct. 29th, 1891.²⁾

As a test of the accuracy of the above equation, which was

1) F. Omori: On the After-shocks of Earthquakes; Jour. Sc. Coll., Vol. VII.

2) F. Omori: 16.

**Fig. 11 Time Variation of the Frequency of the Mino-Owari
After-shocks. (Gifu).**



x = Time interval of 12 months.

y = Number of earthquakes at Gifu during the 12 months
denoted by x .



published in 1894, the seismic frequencies at Gifu for 1898 and 1899 calculated by it may be compared with the numbers of the earthquakes actually observed there during these two years. Thus the equation in question gives for the theoretical total numbers of after-shocks at Gifu for the two years the numbers 66 and 57 respectively. It is, however, to be remembered that the equation has been deduced simply from the observations at Gifu during the first 5 days and is not affected by ordinary earthquakes or those which are not after-shocks of the Mino-Owari earthquake. Hence for the theoretical numbers of all earthquakes at Gifu during the two years under consideration, the above must each be increased by the mean annual seismic frequency at Gifu in ordinary years, which was about 18.3. Thus the calculated earthquake numbers come out finally to be 84.3 and 75.3 respectively, or together 160. Actually there were 101 and 62 earthquakes respectively in 1898 and 1899, or 163 during the two years; these numbers agreeing with the calculated results as closely as may be expected.¹⁾

Similar calculations have been made, with equally satisfactory results, for the after-shocks of the Hokkaidō earthquake of March 22, 1894,²⁾ and those of the great Ansei earthquake of Dec. 24, 1854.³⁾

Dr. Enya has recently arrived at another equation expressing the relation between the time and the frequency of after-shocks,

1) F. Omori: Note on the After-shocks of the Mino-Owari Earthquake of Oct. 28th, 1891; E. I. C. Publ., No. 7.

2) F. Omori: Note on the After-shocks of the Hokkaidō Earthquake of March 22nd, 1894; E. I. C. Publ., No. 4.

3) F. Omori: 2nd report on the After-shocks of Earthquakes; E. I. C. Hō., No. 30.

which also gives results agreeing tolerably well with the observed numbers.¹⁾

(E) **Geographical Distribution of Earthquakes.**

Destructive earthquakes.

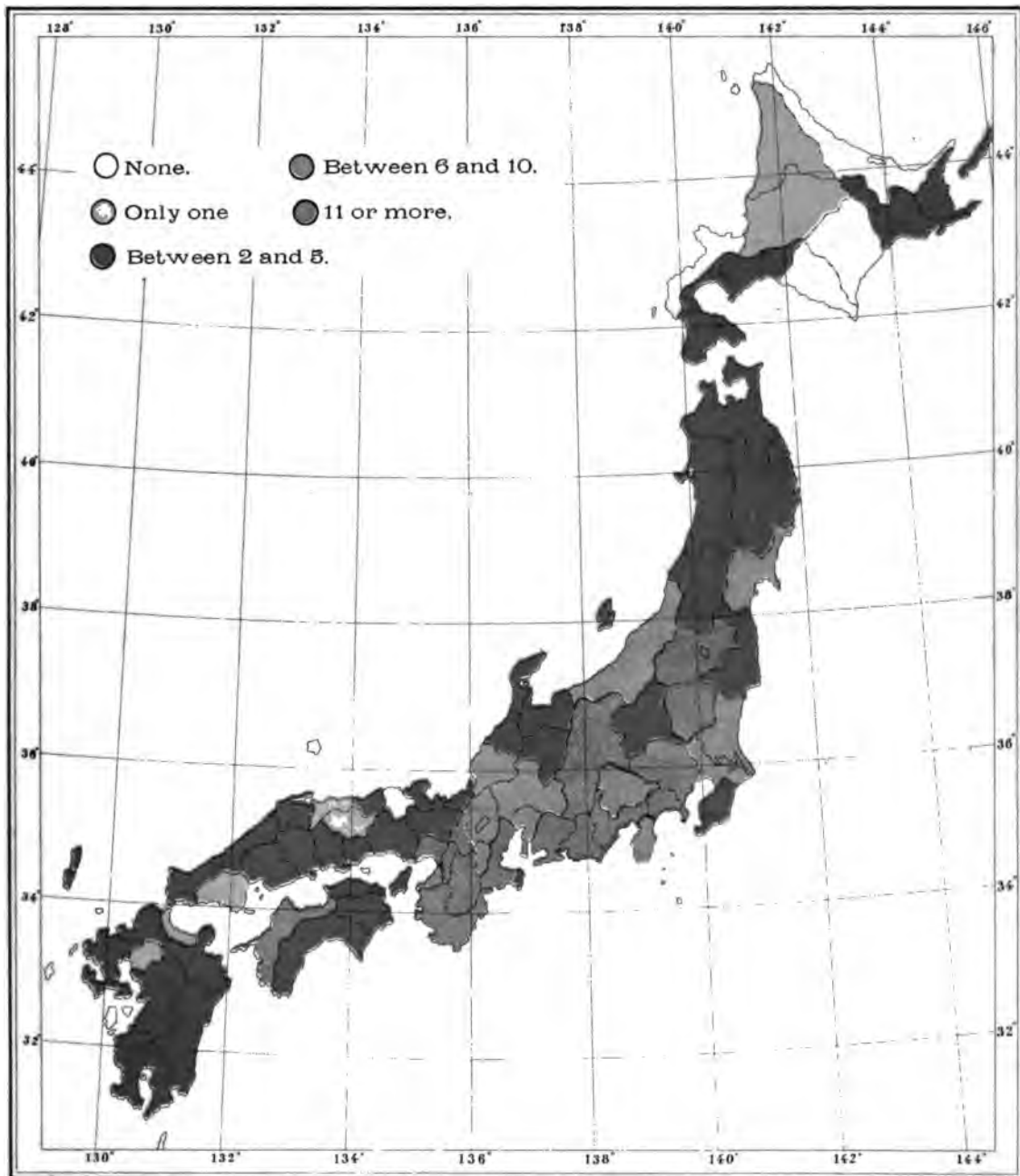
25. Frequency. The geographical distribution of the destructive earthquakes from the earliest times (5th century) down to the present day is shown in fig. 12. No destructive earthquake has occurred in the seven provinces of Iki, Oki, Tajima, Shiribeshi, Kitami, Hitaka and Tokachi; only one each in the seven provinces of Chikugo, Buzen, Suwō, Hōki, Mimasaka, Ishikari and Teshio; more than eleven in each of the fourteen provinces of Yamashiro, Yamato, Kawachi, Settsu, Kii, Ise, Shinano, Mikawa, Tōtōmi, Suruga, Sagami, Musashi, Shimotsuke and Iwashiro; between six and ten in each of the thirteen provinces of Iyo, Izumi, Iga, Ōmi, Echizen, Mino, Owari, Kai, Izu, Shimōsa, Hitachi, Echigo and Rikuzen; and between two and five in each of the remaining forty-two provinces.²⁾

26. The Area of Earthquake Disturbances. Let us for the sake of convenience distinguish destructive earthquakes, according to the magnitude of the area of disturbance, into two kinds, namely, *local* earthquakes, in which the area of destructive motion was confined to only one province, and *non-local* earthquakes, in which the area extended over several provinces. According to this convention, the 223 destructive earthquakes may be divided into 149 local and 74 non-local ones, the ratio of these two numbers

1) M. Enya: On the After-shocks of Earthquakes; E. I. C. Hō., No. 35.

2) F. Omori: Notes on the E. I. C. Catalogue of Japanese Earthquakes; Jour. Sc. Coll., Vol. XI. Notes on great Earthquakes in Japan; E. I. C. Hō., No. 32.

Fig. 12. Distribution of Destructive Earthquakes in Japan
 (Formosa and Lyū Kyū excepted)
From the 5th century to the present time.



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being as 2:1. Further, it is to be noted that the provinces of Ōsumi, Satsuma, Higo, Hizen, Chikuzen, Tsushima, Iwami, Izumo, Kaga, Noto, Sado, Echigo, Shinano, Shimotsuke, Iwashi-ro, Uzen, Ugo, Ishikari and Teshiwo were generally disturbed by local shocks; non-local ones originating very rarely in these provinces, with the exceptions of Shinano and Echigo. On the other hand, Hyūga, Bungo, Tosa, Kii, Mino, and the provinces of Kinai and Tōkaidō were often disturbed by great non-local shocks, of which the origins were generally situated off the eastern coast of Japan, and which were probably caused by faults formed parallel to the latter.

The three north-eastern provinces of Rikuzen, Rikuchū and Nemuro were often disturbed by great earthquakes of sub-oceanic origin. The areas of destructive motion in these cases seem never to have extended to the south of Hitachi and the Peninsula of Kazusa and Awa. Now, as is well known, the group of the Japanese islands forms an arc, with its concavity turned towards the Japan Sea, and the general geographical distribution of destructive earthquakes in Japan may be summarised as follows. The provinces on the concave or Japan-Sea side of the arc were disturbed almost exclusively by local shocks; while those on the convex or Pacific side of the arc were often disturbed by great non-local ones, whose origins were situated in the Ocean, sometimes accompanied by "*tsunami*." Of the provinces in the central portion of the Main Island, Mino, Shinano, Shimotsuke and Iwashi-ro often became the seats of local destructive earthquakes. But the two other provinces of Kōtsuke and Hida were very seldom disturbed by destructive earthquakes, and form, together with Tajima and a few provinces in Sanyodō, the regions seismically most stable in the Main Island.

27. Origin. What has been said above relates to the frequency of destructive earthquakes in the different provinces of the Empire. Examining now the 223 large shocks recorded since the earliest times with respect to their origins, the approximate results are as follows:—

Origin in the Pacific,...	...	...	...	...	47 earthquakes.
,, , Japan Sea, ...	...	...	...	...	17 ,,
,, , Inland Sea, ...	...	...	...	...	2 ,,
,, inland, ...	...	...	...	...	114 ,,
(,, obscure, ...	...	...	...	...	43 ,,)

Thus the numbers of the earthquakes of the Pacific, Japan sea, and inland origins were as 3:1:7.

Of the 47 destructive earthquakes of Pacific origin, 23 were accompanied by *tsunami* which often caused much greater damage than the earthquakes themselves. From fig. 13, which shows the distribution of the *tsunamis* (accompanying earthquakes) along the coast of Japan, it will be seen that, they were almost entirely confined to the Pacific coast, the only exceptions being two along the coasts of Echigo and Sado; the provinces most often devastated were Izu, Awa (in Shikoku), Settsu, Tōtōmi, Rikuchū, and Mutsu.

Among the 223 destructive earthquakes, there were 10, which were especially great. Of these, seven originated off the south-eastern coast and were each accompanied by destructive *tsunami*; while the remaining three were of inland origin and shook the central parts of the Main Island.

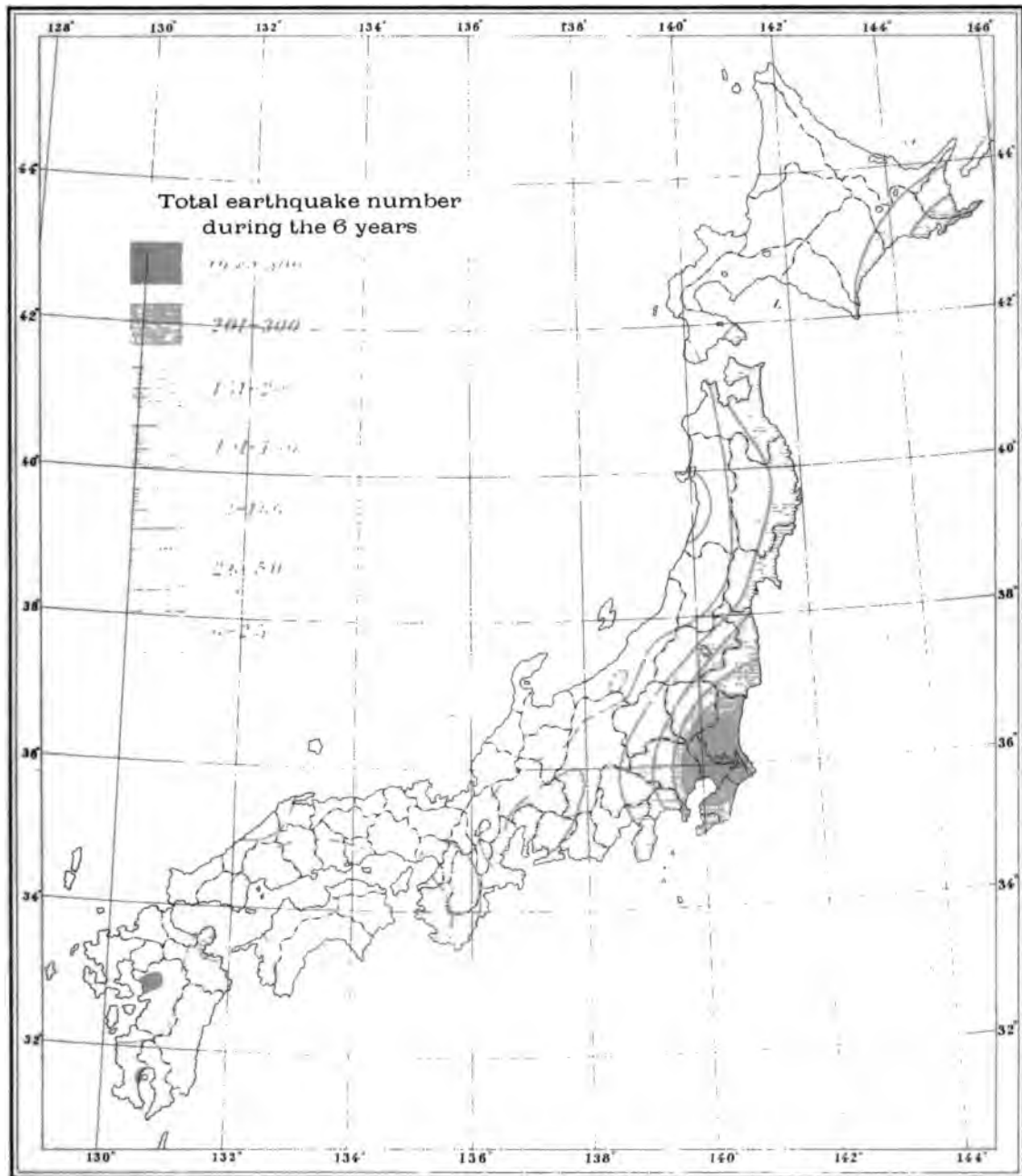
The greatest among the ten earthquakes above referred to was that of the 4th year of Hōei (Oct. 28, 1707), the destructive area including the eastern part of Kyūshū, the Island of Shikoku, and the southern part of the Main Island between the province of

Fig. 13. Map showing the Distribution of the "Tsunamis"
accompanying Earthquakes.
(From the 5th Century to the present time.)





Fig. 14. Map showing the Frequency of Earthquakes, during the six years between 1885 and 1890.



Harima on the west and the provinces of Kai and Suruga on the east.

Ordinary earthquakes.

28. *Frequency.* Fig. 14 shows the frequency of earthquakes in the different parts of Japan during the six years between 1885 and 1890.¹⁾ As there was no destructive earthquake during this interval, except that of Kumamoto, July 28, 1889, the map may be regarded as fairly showing the seismic state of the country in *ordinary* years. It will be observed that earthquake frequency is much greater along the eastern coast of the Islands than along the western.

29. *Origin.* The distribution of the earthquake origins in Japan seems to have a close connection with the curvilinear form of the country; they are arranged approximately in two systems which are respectively parallel and normal to the arc formed by the Japanese islands.

Tsunami.

30. As stated above [Art. 27], a large number of destructive earthquakes of Pacific origin were accompanied by *tsunami*. One of the most destructive seismic *tsunamis* in recent years took place on June 15th, 1896, the whole north-eastern coast of the Main Island for a length of 250 miles being devastated. A report of this catastrophe is given in E. I. C. Hō., No. 11, by Dr. T. Iki.²⁾

1) The map is taken from the *Earthquake Reports*, published by the Central Meteorological Observatory.

2) See also Dr. A. Imamura's Note "On the great tsunami of 1896," in E. I. C. Hō., No. 29.

In E. I. C. Hō., No. 34, Prof. Omori gives the result of the examination of the tide-gauge diagrams at several stations on the Pacific coast of Japan and arrives at the conclusion that different parts of the coast have their proper period or periods of waves, that is to say, each particular portion of sea coast is virtually a fluid pendulum whose boundaries are determined by the form of the bottom and the contour of the shore line. Accordingly, the wave period or periods at a given place on a given coast remain constant in all the *tsunamis*, irrespective of the origin or cause; a destructive *tsunami* consisting simply in the amplification of the amplitude of the wave motion existing more or less at all times, in consequence of a strong submarine earthquake, a storm, or some other agency. Seismic *tsunamis* occur very often along the Pacific coast, each strong submarine earthquake being always accompanied, or rather followed, by some amount of sea water disturbance. A seismic *tsunami* is caused, according to Prof. Omori, by the movements communicated from the sea bottom to the superincumbent water; a very big *tsunami* taking place when the earthquake focus is at the sea bottom itself or at a very small depth below it. [See also Art. 100.]

CHAPTER III. INSTRUMENTAL INVESTIGATIONS.

31. In order to obtain a more accurate knowledge of the nature of the earthquake movements, it is necessary to have instruments which will enable us to obtain records of the movements while they are actually taking place, that they may be studied at leisure afterwards; these records must not only be very accurate, but must indicate movements which we could not have perceived at all without them. Hence from the first, the devising and improving of seismometers and seismographs have engaged the attention of seismologists.

The E. I. C. has spared no pains in order to secure good seismographs, and in making careful observations with them. The records so obtained have been carefully examined, and many important conclusions have been deduced, concerning the vibrations of the earth particles. I shall first give a short account of the instruments.

(A) Seismographs and Seismometers.

32. It would be too long and out of the scope of the present address to give an account of various contrivances and instruments that have been suggested or been actually used, interesting as it would be. I shall here simply give a short description of the seismographs or seismometers, actually set up at present in the Seismological Institute of the Tōkyō Imperial University; most of the various instruments have there been tried, and those now there have been left, as the fittest, to survive.

As it is not easy or convenient to take a record of movements of an earth particle in three dimensions at once, we take them separately for the horizontal and the vertical motions. We thus have two divisions of seismographs, one for recording the motion in the horizontal plane, and the other for the vertical motion.

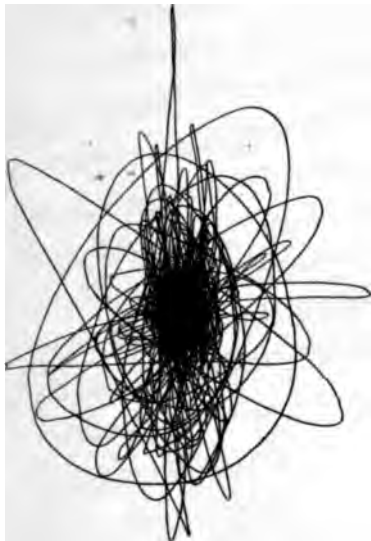
Instruments for recording the horizontal motion.

33. The essential in all seismographs is a steady point, a point which shall not be displaced by the shock, and which is in a state of neutral equilibrium, so that when the shock comes and the earth moves, this point will remain at rest and therefore be displaced relatively to the earth; being in neutral equilibrium, it will remain in this position. Thus as the earth moves, this point always remains in its original position, and a pointer attached to this point will trace out on a surface fixed to the earth the movements of the point relatively to the earth, that is, the motion of the earth particle. Practically of course it is impossible to obtain a point which is absolutely steady or in absolutely neutral equilibrium. We must be content with an approximation to these conditions.

34. *Duplex Pendulum Seismometer.*¹⁾ This is a "a combination of a common with an inverted pendulum. The common pendulum is stable, the inverted pendulum with a rigid pivoted supporting rod is unstable: by placing an inverted pendulum below a common one and connecting the bobs so that any horizontal

1) For full description of this instrument, see Ewing, *Seismological Notes*, *Trans. Seism. Soc.*, Vol. V; Ewing, *On a Duplex Pendulum Seismometer with a single bob*, ditto, Vol. VI; Sekiya, *On Prof. Ewing's Duplex Pendulum Seismometer*, (the actual instrument being of the construction described in this paper), ditto, Vol. VIII; Milne, *Modern forms of Pendulum Seismometer*, ditto, Vol. XII; Ewing, *Earthquake Measurements*, *Memoirs of Science Dept. of Tokyo Univ.*, No. 9.

Fig. 13. Duplex Pendulum Seismograph.

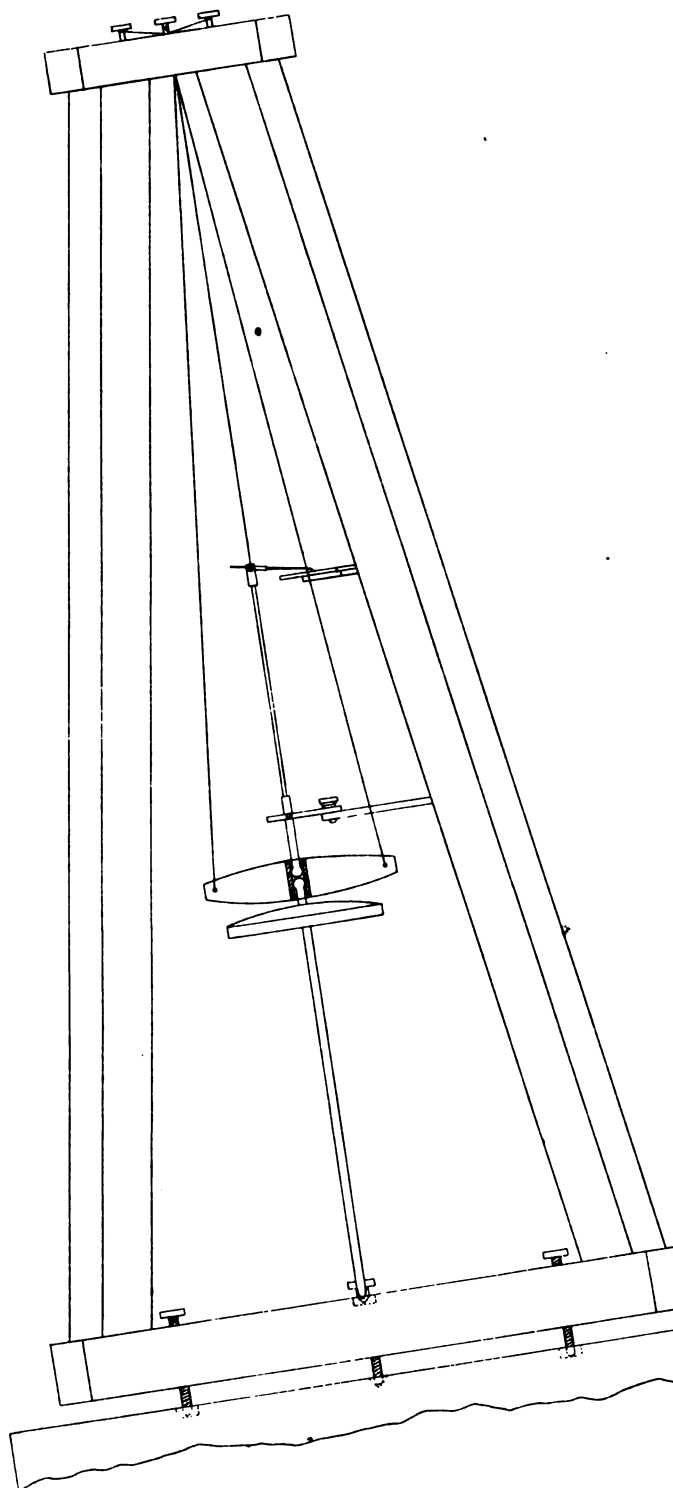


Earthquake of Aug. 27, 1897.



Earthquake of April 20, 1896.

Multiplication 7 times.



displacement must be common to both, we may make the equilibrium of the jointed system neutral or as feebly stable as may be desired." A pointer attached to the steady point so obtained is made to trace out the motion on a stationary smoked glass plate. [See fig. 15.]

The record thus obtained, however, being statical is not of very great use in accurate measurements. It is more convenient to obtain the records of the horizontal motion decomposed into two rectangular components, such as N-S and E-W. This is the case in all other instruments.

35. *Ewing's Bracket or Horizontal Pendulum Seismograph.*¹⁾ The chief parts of this instrument are shown in fig. 16. [See also fig. 21.] The steady point or rather line is furnished by the axis *dd* of the heavy bob B of the pendulum in the form of a cylinder or a truncated cone, pivoted along its axis *dd* to a frame, which itself is pivoted about a nearly vertical axis *ac* to a stand fixed to the base plate; the whole thus forms a horizontal pendulum turning about this axis. The axis of the bob is the instantaneous axis corresponding to the axis of support. Thus when the shock comes, in the plane of the axes the pendulum simply suffers a displacement as a whole, but if the ground moves through any small distance horizontally and perpendicularly to this plane, then the system turns about the fixed axis and remains in that position. A pointer attached to this traces out this motion of the mass relatively to the earth multiplied any required number of times, on a revolving smoked glass plate.

Two such pendulums placed at right angles to each other will trace out the rectangular components of the earth motion.

1) Ewing: On a New Seismograph for Horizontal Motion, Trans. Seism. Soc., Vol. II. Also Ewing, Earthquake Measurement: Memoir of the Sc. Dept., No. 9.

This instrument was first publicly described by Prof. Ewing before the Seismological Society of Japan on Dec. 22nd, 1880.

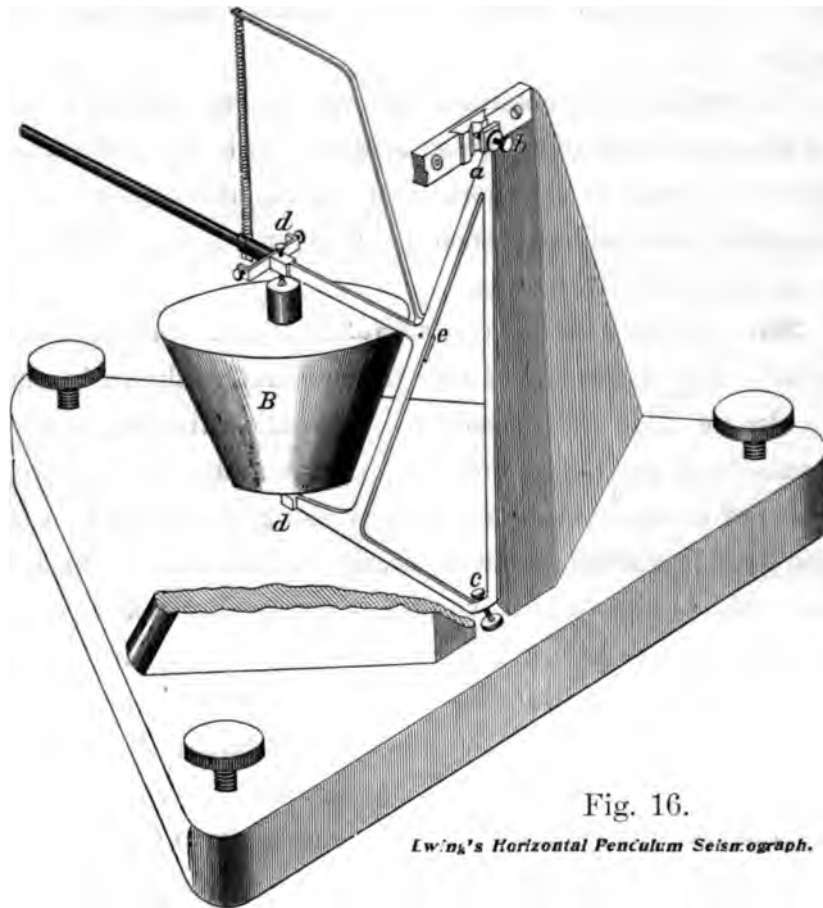


Fig. 16.

Ewing's Horizontal Pendulum Seismograph.

36. In the actual instruments, various modifications have been introduced which experience and a fuller knowledge have shown to be desirable. There are several sets of the instruments of this type, set up in the Institute, differing more or less in their arrangements. In the usual form, the pendulum has a short period of about $2\frac{1}{2}$ seconds and can therefore be relied upon only for ordi-

nary earthquake motion. In others, one of which was specially designed by Prof. Sekiya, the period is much longer, and the distance between the axes much greater, thus enabling us to get reliable records of strong earthquakes. In two of them, the record is taken on a revolving glass plate according to Prof. Ewing's original design, while in others it is taken on a band of smoked paper wound round a revolving drum having at the same time a slow motion of translation in the direction of its axis: the latter form suggested by Prof. Milne is in many respects more convenient than a glass plate, but the objection to it is that it increases the friction of the pointer; by various devices, however, this has been made so slight, as to make this arrangement preferable.

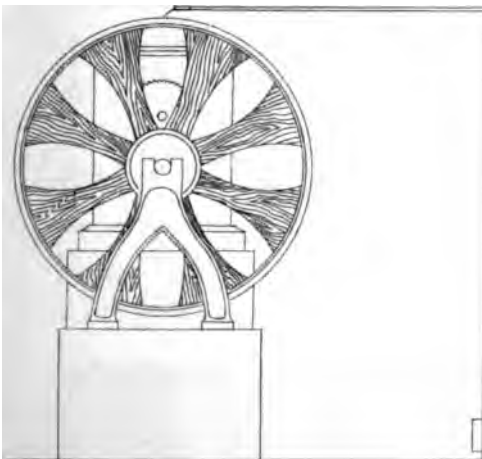
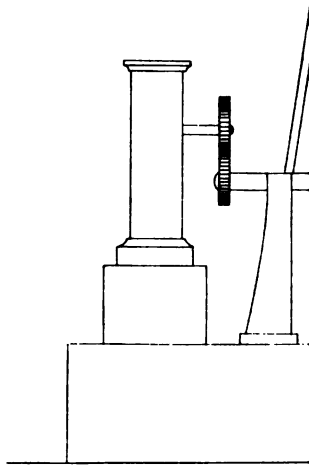
The glass plate or the drum is started by an automatic starter when the shock comes, and is kept revolving by clockwork. The starter is either electrical or mechanical. The electrical starter is nothing more than a modification of Palmieri's circuit closing seismoscope and consists of an ordinary short pendulum suspended from the top of a fixed frame; the bob is a cylinder having a small conical socket in its lower surface. A wire fits into this socket, and is held in a vertical position and pressed against the bob, by a thin narrow strip of steel, projecting from the side of the frame and attached to the wire near its upper end. The lower end of the wire, which is connected with one pole of an electric battery hangs over the center of a ring of mercury which is connected with the other pole of the battery. The bob is displaced by a shock, and with it the upper end of the wire, which then moves about the point of attachment of the steel strip, thus causing the lower end to come in contact with the mercury: this closes the circuit and an electric current is started, which by means of an electro-magnet rings a bell and sets free the clockwork turning the plate or the drum.

The mechanical starter is used for strong earthquake seismographs, and consists usually of a ball slightly flattened at one point and resting on a platform. When a sufficiently strong shock comes, the ball rolls off the platform, thereby setting free the clockwork. Recently, a very ingenious starter has been devised by Dr. A. Imamura, assistant professor of Seismology, which is described in the E. I. C. Publ., No. 7.

37. The starter sets free at the same time a pendulum which by its ticking marks the intervals of time from the start. In connection with the starter, there is also an arrangement for marking the time of starting on the face of a clock, by means of small projections at the ends of the hour, minute and second hands, tipped with a small piece of sponge dipped in red ink; at the same time as the starting of the clockwork, the face of the clock is jerked forward, comes in contact with the sponge and is marked. The time thus marked will depend of course on the sensibility of the contact-maker and is necessarily not very accurate, so that at present it is not used at the Institute.

A copy of a part of the diagram of the destructive Tōkyō earthquake of June 20th, 1894, taken with Prof. Sekiya's instrument is given in fig. 28.

38. Prof. Gray, formerly of the Kōbu Daigakkō (the Engineering College) suggested a modification of the horizontal pendulum: instead of the bob being supported on a rigid framework, he proposed to substitute a heavy mass suspended by a wire from a point in a fixed post and held out by a rigid strut with one end pivoted on a point directly below the point of suspension, thus forming a *conical pendulum*. This is the form adopted in the Gray-Milne Seismograph described in the Phil. Mag. for April, 1887, and also in the Trans. Seism. Soc., Vol. XII.





39. *Omori's Horizontal Pendulum Seismograph.* All the instruments so far described, including Prof. Gray's Conical Pendulum instrument, will record ordinary or strong earthquake motions, but fail to give reliable records of very small or slow motions accompanying earthquakes, and of pulsatory oscillations. Prof. Omori has adopted the conical pendulum and has constructed a seismograph, which can be made to give records, not only of earthquakes, both ordinary and strong, but also of very small or slow movements of earth accompanying earthquakes or due to distant earthquakes, of small pulsatory oscillations, and of slow changes of level.

The chief parts of one of these instruments are shown in fig. 17. The bob of the pendulum is a cylinder of thin brass, *a*, filled with lead, and say about 10 kgm. in weight, attached a little above its centre of gravity to a strut, *b*, consisting of an iron tube furnished with a sharp steel point pivoted in a conical steel socket fixed to the stand at *c*. The bob is hung by two fine steel wires, *e*, from a point in the stand directly above the socket, the lower ends of the wires being attached to a pair of hooks *f* pivoted to the bob at the ends of its central diameter normal to the pendulum plane. The attachment of the upper end of the wire to the stand is made by an arrangement, by means of which very delicate adjustments of the pendulum, vertical and horizontal, can be made. The distance between the points of suspension and of support is about 1 metre, while the length of the strut is about 75 cm. The period of the pendulum can be made very long, over 60 sec., if desired, so that the proper motion of the pendulum can be clearly distinguished from the real motion of the earth.

In order to reduce the friction at the attachment of the writing pointer, and between the writing pointer and the record receiver,

as much as possible, Prof. Omori has devised a special form of the pointer and a special method of attaching it to the steady point. The writing pointer consists of a small steel axis to which a light lever is attached rigidly; the longer arm is of aluminium, while the shorter arm is of brass and forked. By means of a small counterpoise, the centre of gravity of the whole pointer is made to coincide with the axis. The whole lever is supported by the axis, pivoted between two steel sockets, which is fixed to a stand and can be adjusted in proper position. Between the two limbs of the fork of the shorter arm fits exactly a highly polished steel axis which is a prolongation of the central line of the bob of the pendulum and is pivoted in a frame fixed to the upper end of the bob.

To a small U-shaped frame of brass at the end of the aluminium arm of the pointer, is hinged an exceedingly light writing index made of thin triangular piece cut from a watch spring. The point of the index rests on the record receiver, which is a band of smoked glazed paper, wound round a drum. The drum is turned round by clockwork at any required rate differing according to the particular kind of the earth motion that we wish to observe, say from 3 cm. per minute to 3 cm. per hour; the drum has at the same time a slow motion of translation in the direction of its axis. The record is continuous, differing in this important respect from the instruments previously described; and the rotation of the drum is marked by a time ticker which is in circuit with a chronometer.

Instead of hanging and supporting the pendulum from a strong stand, which is then fixed to the top of a stone or brick column, we may make use of the wall of solid buildings, as has actually been done in the Earthquake-proof House in the University ground. [Art. 108.]

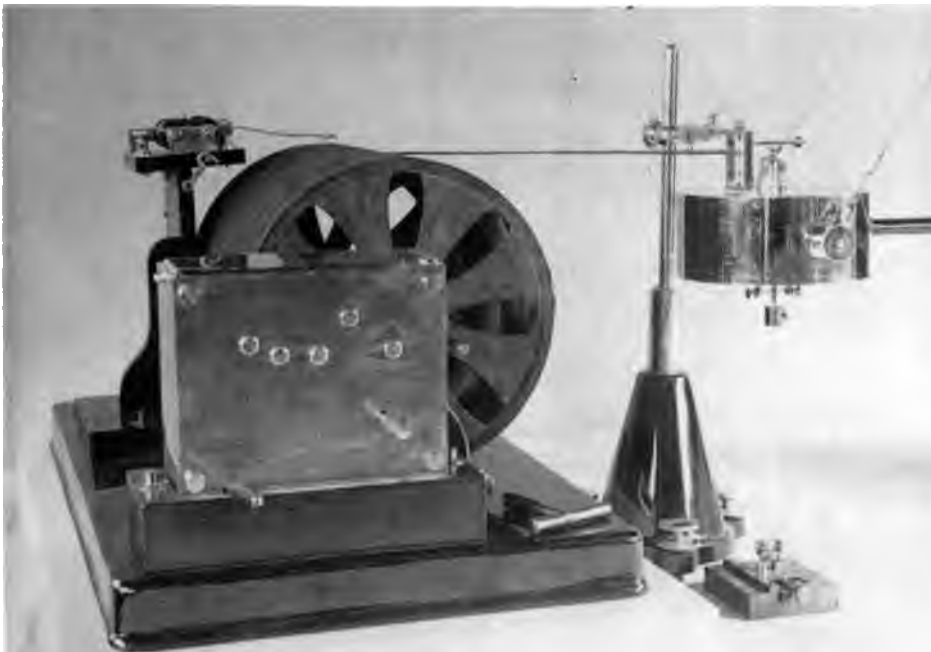
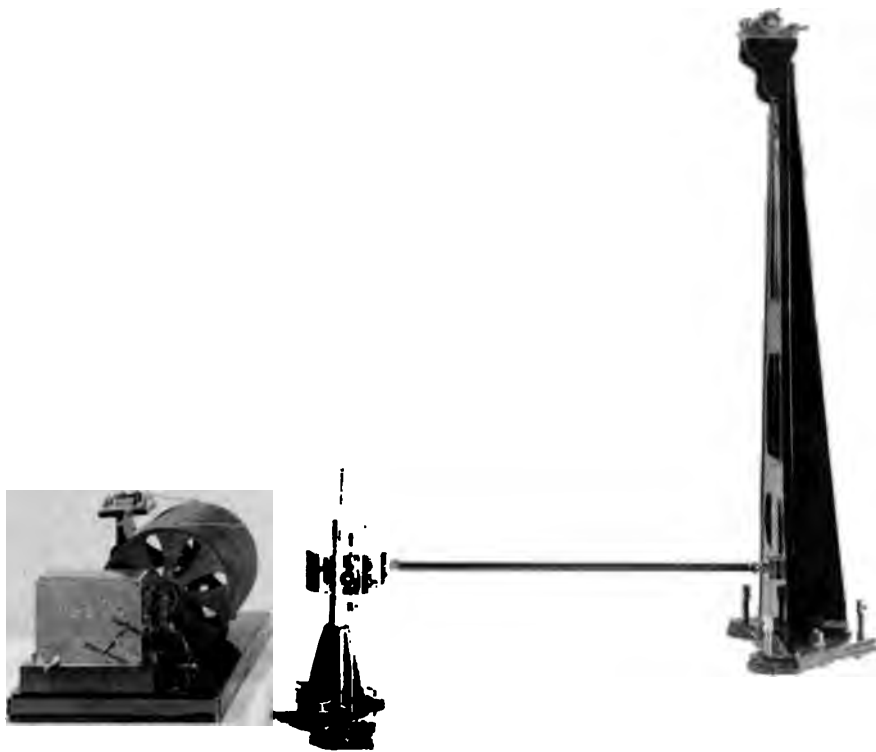


Fig. 18. Omori's Horizontal Pendulum Seismograph.

For a full description of this instrument, see the Jour. Sc. Coll., Vol. XI, or the E. I. C. Publ., Nos. 5 and 12.

40. In the latest form of this instrument, Prof. Omori has made an important modification by introducing the principle of Duplex pendulum. In this form, under the cylindrical bob, there is an inverted pendulum, consisting of a small metallic disk, whose mass is small compared with that of the cylinder, supported on a light aluminium tube pivoted at its lower end in a conical socket and connected with the cylinder at its upper end in such a way that the friction is reduced to a minimum. This arrangement makes the equilibrium of the compound bob still further approximate to the neutral, so that with the vertical distance between the points of suspension and support, and the length of the strut each 1 meter, the period can be made as long as 1 minute, and the multiplication 30 times, without difficulty.¹⁾ [See also fig. 18.]

An instrument of this type having a period of about 30 sec. and a multiplication of 120 times is among the exhibits of the E. I. C. at this Exposition.

41. *Prof. Tanakadate's Parallel Motion Seismograph for Strong Earthquakes.* Prof. West has suggested the use of Watt's parallel motion arrangement as suitable for a seismograph and actually constructed an instrument on this principle.²⁾

Some time ago, Prof. Tanakadate has constructed a strong earthquake seismograph by using the same principle in a different way. In this instrument, a heavy mass is pivoted on a rectangular frame which forms the connecting link of a Watt's parallel mo-

1) A full description of this instrument has not yet been published, but for an abstract, see Su Buts. K. G., Vol. II, No. 8.

2) West: Suggestion for a new type of Seismograph; Trans. Seism. Soc., Vol. VI.

tion arrangement. The radius rods are pivoted on to the base plate of the instrument by vertical axes which are slightly inclined towards each other in order to give a small amount of stability to the horizontal motion of the suspended mass. The frame is linked to the radius rods by means of Hooke's joints with the planes of the cross pieces at right angles to each other, so as to make the relative motion of the links kinematically unique, though it deviates from being strictly two dimensional.

A photograph of this instrument with Prof. Tanakadate's Vertical Motion Seismograph is shown in fig. 22 [see Art. 46].

42 *Photographic Record Horizontal Pendulum Seismographs.* In all the instruments described above, the record is taken mechanically, thus introducing friction at several points, although it has been reduced to a very small quantity in Prof. Omori's seismograph. The record may be obtained photographically by throwing the light reflected from the steady point on a sensitized paper; this does not introduce friction like a pointer, but on the other hand, the chief objection to almost every photographic recorder at present in use is the very slow rate of motion of the photographic paper, which renders it unfit for recording short period motion.

The E.I.C. had a Rebeur-Paschwitz horizontal pendulum¹⁾ slightly modified, constructed for it by Messrs. Repsold & Sons, and observations were made with it for some time. At present it is not set up for want of a suitable room.

The Committee has also purchased and set up Prof. Milne's Horizontal Pendulum Seismograph in 1899, in compliance with the request of the British Association for the Advancement of

1) For a description of the original pendulum see Nova Acta der Kais. Leopold-Carol. Deutsch. Akademie der Naturforscher, Bd. LX, No. 1., 1892.

Science, forwarded through the British Government, the object being to establish a systematic observation of the motion of the earth's crust with similar instruments all over the world. The instrument is at present housed in a small shed built for it; and the result of the observation is reported to the Seismological Committee of the British Association. An examination of the records taken with this seismograph between July, 1899, and Dec., 1902, by Dr. Imamura in whose charge the observation is placed, is given in the E. I. C. Publ., No. 16.¹⁾

Instruments for recording the vertical motion.

43. A vertical motion seismograph presents a difficulty not met with in a horizontal motion seismograph, for here we have gravity acting in the direction in which the freedom of motion is to be retained. The first successful attempt made was the Helical Spring Seismograph²⁾ of Prof. Gray. The essential point of this instrument is a helical spring, supporting a lever which turns about a knife edge at one end, and is weighted at the other end with a lead ring. This arrangement by itself makes the period of oscillation of the mass greater in the ratio of the square roots of the arms of the lever, than if the mass were hung directly from the spring. But Prof. Gray has added an ingenious device by which the equilibrium is made still nearer to the neutral: from the end of the arm is suspended a small trough pivoted and partly filled with mercury. Now if the mass be raised or lowered, the end of the trough is relatively lowered or raised, and the mercury,

1) Also see E. I. C. H5., No. 35.

2) Gray: On a Seismograph for recording the Vertical Motion; Trans. Seism. Soc., Vol. III, or the Memoir of the Science Dept, Tōkyō Univ. No. 9.

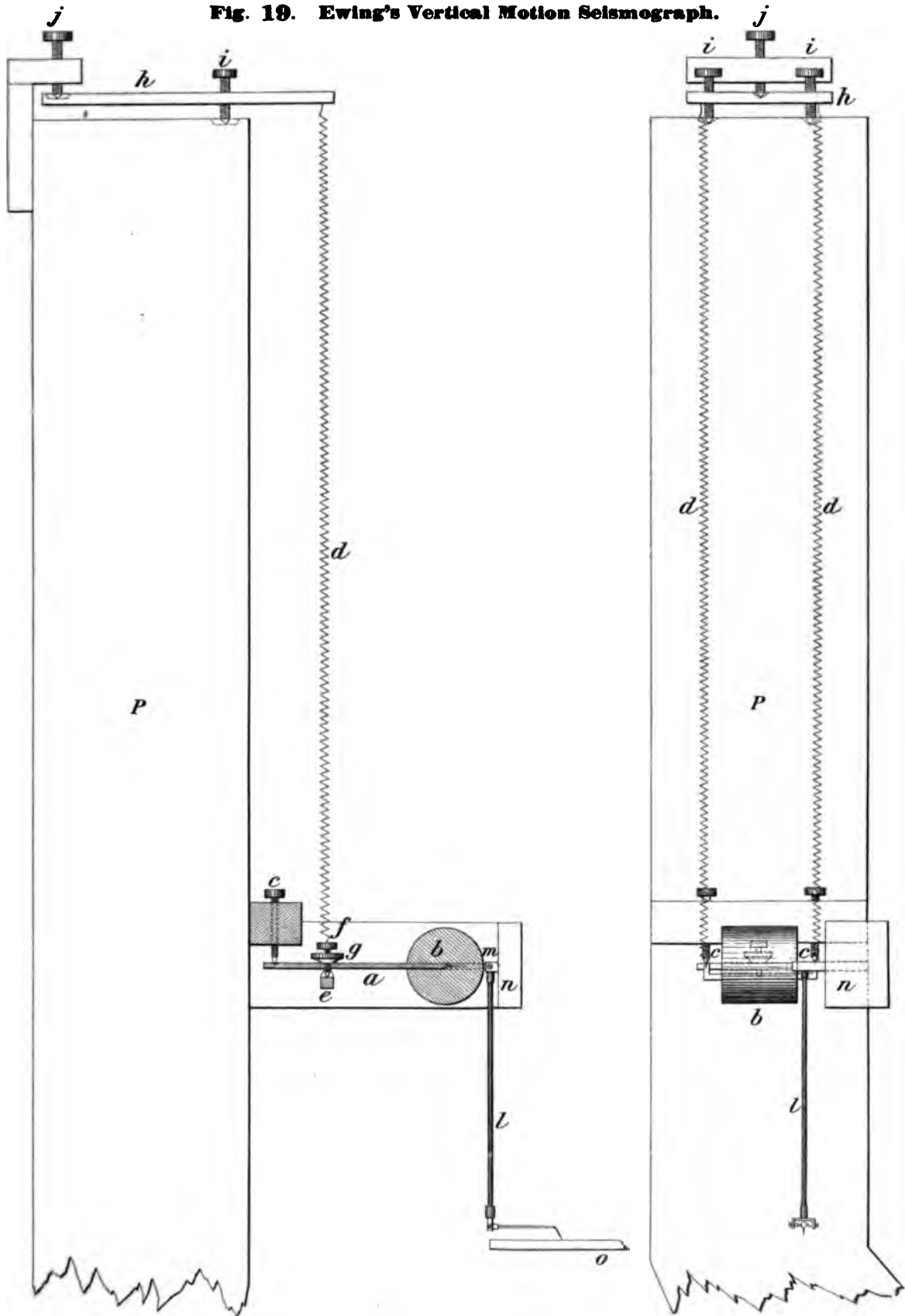
running backwards and forwards tends to increase or diminish the moment about the axis, thus counterbalancing the increase or decrease of the tension of the spring, and so to make the equilibrium neutral.

44. *Ewing's Vertical Motion Seismograph.* Prof. Ewing has adopted Prof. Gray's principle and invented another method of compensation. The chief parts of this seismograph is shown in Fig. 19. The lever is a stout brass plate *a* loaded at the outer edge with a cylinder of lead *b*. A pair of steel points projecting from the fixed pier or post fits into a conical socket and a V slot, cut into the plate near its inner edge, so forming a horizontal axis about which the lever turns. A pair of helical springs *dd*, suspended from a projection in the pier, hangs vertically and is connected at the lower end by a small transverse bar *e*, at the center of which is a conical socket; in this socket, rests the screw *f* projecting downwards from the plate, the length of the projection being adjustable. When the cylinder is lowered or raised, the point of the screw *f*, that is, the point of application of the tension of the spring is moved slightly away from, or towards, the axis about which the lever turns, thus increasing or diminishing the leverage and compensating for the change of tension.

A writing pointer is attached to the bob near its axis, and hanging vertically downwards writes the motion transformed into a horizontal one on a plate or a drum.

45. This instrument, and two bracket seismographs [Art. 35] placed at right angles to one another for the two rectangular components of the horizontal motion, arranged together on a stand so as to write their records on the same drum, form the usual seismographic equipment for local meteorological stations through-

Fig. 19. Ewing's Vertical Motion Seismograph.



out Japan. This I shall call the ordinary Ewing-Gray-Milne seismographs. A photograph of this is shown in fig. 21.

46. *Prof. Tanakadate's Spiral Spring Seismograph.*

The construction of this instrument will be seen from fig. 20. The steady point is furnished by the heavy cylinder M , which is supported on two frameworks by having its axis passing through a pair of slots in the arms $L L$ of the one, and a pair of holes in the arms $L' L'$ of the other: the transverse piece at the other end of each framework forms the axle $A A'$, about which a spiral spring is wound, and which is supported on two vertical pieces $B B'$; the other end of the spring is fixed to the inside of the cylindrical box $D D'$ containing the spring. Each spring is wound up so that it will just support one half of the weight of the bob. The bob will

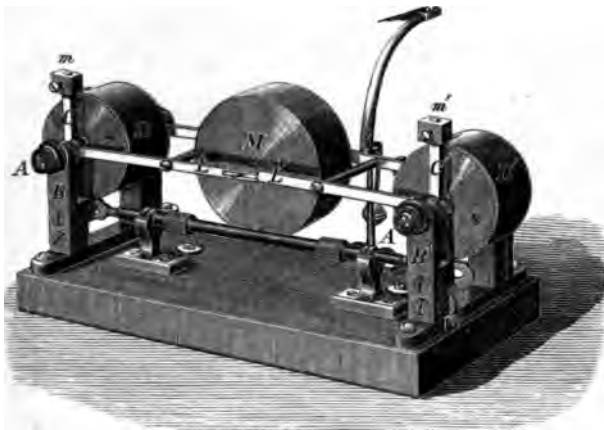


Fig. 20. *Tanakadate's Spiral Spring Vertical Motion Seismograph.*

thus be in a stable equilibrium, performing small vertical oscillations whose period will depend upon the weight of the mass and the force of restitution of the spring. By attaching a small vertical bar $C C'$ to the axle $A A'$ of the spring, and putting a

small sliding weight $m m'$ on it, the system can be brought into a state of neutral equilibrium on adjusting the sliding weight to the proper height. For the full description of this instrument, see E. I. C. Publ. No. 7.

The first working instrument of this type was exhibited at the

general meeting of the Tōkyō Sugaku-Butsurigakkwai (Mathematical and Physical Society) on June 6th, 1898. It was exhibited at the Paris Exposition of 1901, by the E. I. C. A photograph of this instrument with Prof. Tanakadate's parallel motion seismograph is shown in fig. 22.

47. Thus I have given a short description of seismographical instruments, most of them actually in operation in one or more of the following seismological stations: namely, the laboratory of the Seismological Institute of the Tōkyō Imp. Univ., the Earthquake-proof House of the E. I. C., the Seism. stations of the E. I. C. in direct telegraphic communication with the above laboratory, the Central Meteorological Observatory, the Kyōto Imp. Univ., local meteorological stations, &c. For their full description, you are referred to the publications mentioned.

It will be seen that after all sorts of contrivances had been tried, Prof. Ewing succeeded in constructing a Horizontal Pendulum Seismograph for recording the horizontal motion of the earth particle in two components, and Prof. Gray in applying helical spring to record the vertical motion. Since then, modifications and improvements in details of construction have been introduced, which subsequent experience has shown to be advisable. But the knowledge of the earthquake motion, which was obtained with them, made something more than mere modifications in details necessary for a further advance. Prof. Omori's latest form of the Horizontal or Conical Pendulum Seismograph with continuous mechanical recorder is a very good seismograph, I do not hesitate to say, the best that we have at present: there is plenty of work that can and will be done with it for the present. But there is still room for increasing the neutrality of equilibrium of the pendulum and diminishing friction between the parts; as to the damping

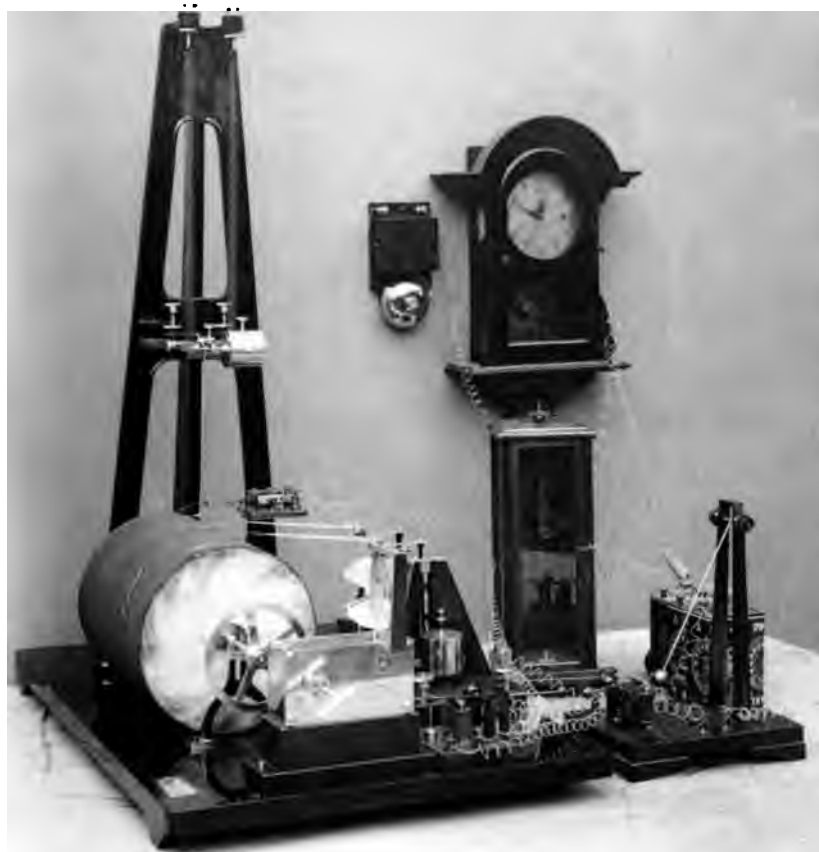


Fig. 21. Ordinary Ewing-Gray-Milne Seismograph.



Fig. 22. Tanakadate's Strong Motion Seismograph.

of the motion of the pendulum, we are of the opinion, that it is neither necessary nor desirable. A photographic recorder that shall be sensitive enough to enable us to move it with a sufficient speed would be a great improvement.

I proceed now to give some of the most important of the conclusions regarding the nature of vibrations of the earth's crust.

48. The motion of the earth's crust as actually observed, consists in general of several sets of waves of different amplitude and period, which may be partly longitudinal and partly transverse, the amplitude and period ranging within wide limits.

We shall find it convenient to divide the motion into two classes: the *sensible*, or that which can be felt as tremblings or shocks; and the *insensible*, or that which can not be felt. These are sometimes distinguished as *Macro-seismic* and *Micro-seismic*, although these terms have also been employed in a quite different sense by some seismologists. In the former, quick vibrations, i. e. vibrations of short period, coexist with slower vibrations, while in the latter, quick vibrations are either absent or extremely minute. The amplitude of some vibrations in the insensible motion is as large as, or even larger than, that of vibrations in small but sensible local earthquakes; they are insensible only because their period is very long, in comparison with their amplitude, and consequently their acceleration small; in fact, the insensible motion is such because its acceleration is small.

It is evident that observations of the sensible and the insensible motions can not be conveniently combined in one and the same instrument, the chief points of difference in the instruments for measuring them being in the multiplication ratio of the record writer and the rate of motion of the record receiver.

The earth's crust being regarded as an elastic medium through which these waves are propagated, the investigation of these waves, of their mode of propagation, and their behavior under various circumstances is a very important problem of pure Seismology, regarded as a branch of Geophysics. To furnish data for these investigations by accurate determination of the nature of these waves is the province of the observational Seismology.

(B) **Sensible or Macro-Seismic Motion.**

49. To this class belong motions of earth, known as *Earthquakes* in the ordinary acceptation of the term. They proceed from an origin at a comparatively small distance from the place of observation, say under 1000 km. I shall state briefly some of the results of the observations of these motions, made chiefly with the ordinary (Ewing-Gray-Milne) seismographs [Art. 45].

The Earthquake Motion as observed with the ordinary

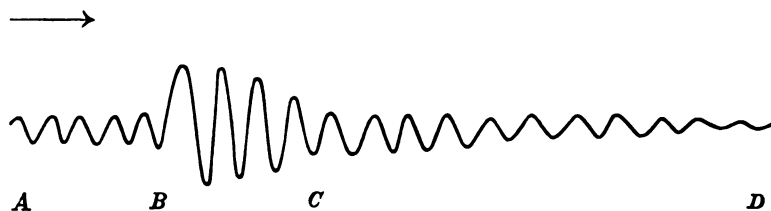


Fig 23. Diagrammatic Representation of the Earthquake Motion.

seismograph begins with vibrations of small amplitude and comparatively short period, these are usually known as the *preliminary tremors*; next come those of larger amplitude, constituting the *Main* and most active part¹⁾; and finally the earth-

1) Usually called the "Principal portion."



quake ends with feeble vibrations, which I shall call the *Tail*¹⁾ of the earthquake.

In each of these three sections, very small quick vibrations or "*ripples*" are often found superposed on comparatively slower vibrations; the latter constitute the chief element of the earthquake motion and may be termed the "main" vibrations in contradistinction to the ripples; the period²⁾ of ripples is a mere fraction of a second, while that of the main vibrations is much longer, say between $\frac{1}{2}$ and 2 seconds. The ripples are found more or less in rocky or hard soil district but are almost entirely absent on soft soil. Examples of seismograms are given in fig. 24.

Intensity.

50. In order to indicate the intensity or magnitude of an earthquake, the Central Meteorological Observatory has adopted the following relative scale of intensity for ordinary or non-destructive earthquakes:—

A *slight* shock is one which is very feeble; a *weak* shock is one whose motion is well pronounced but not so severe as to cause general alarm; and, finally, a *strong* shock is one which is sufficiently sharp to produce small cracks in walls, to throw down bottles on a shelf, etc.

For the discussion of the destructive effects of the earthquake motion, we must have an absolute measure of intensity: we may represent the intensity of the earthquake motion by the maximum acceleration, a , of the earth particle: $a = \frac{4\pi^2 a}{T^2}$, in which

1) Usually known as the "End Portion."

2) Throughout this address, the *period* is used in the sense of the complete period, and the *amplitude* of double amplitude.

$2a$ is the amplitude and T the period, of the maximum vibration, supposed to be simple harmonic.

For ordinary non-destructive earthquakes, this maximum acceleration a is small; the shock being a severe one when a reaches a few hundred mm. per sec. per sec.¹⁾

The acceleration a just sufficiently strong to be perceptible to us without instrumental aid, that is to say, in the slightest sensible motion, is found to be about 17 mm. per sec. per sec.²⁾

51. *Maximum movements in different earthquakes.*

Fig. 25 shows the relative frequency of the different values of maximum earthquake movements based on the observations of 359 shocks at the Central Meteorological Observatory. It will be seen that the great majority of earthquakes had amplitudes between 0.2 and 0.5 mm. and between 0.6 and 1.0 mm., the numbers of cases corresponding to these two groups being respectively 59 and 19 % of the whole.³⁾

Direction of Motion.

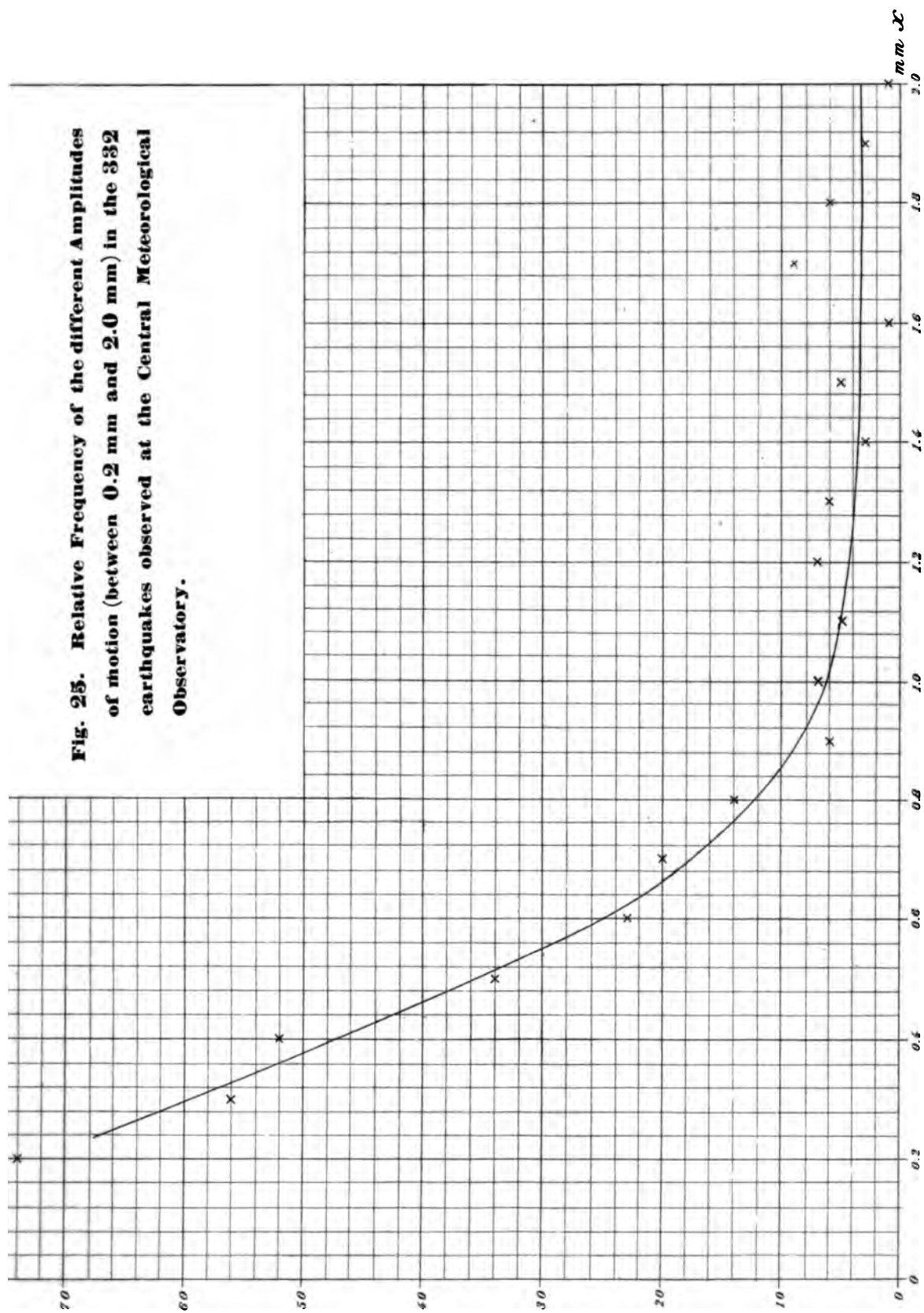
52. By the direction of an earthquake is meant the direction of the greatest vibrations, or that of the principal movements during the earthquake, at a given place. In strong earthquakes, the direction of motion often coincides with the line joining the place of observation with the centre of disturbance, as ought to be the case if the principal vibrations in an earthquake be due to longitudinal waves.

1) For the acceleration in a destructive earthquake see Art. 66.

2) F. Omori: On Earthquake Motions; E. I. C. Hō., No. 41.

3) Loc. cit.

Fig. 25. Relative Frequency of the different Amplitudes of motion (between 0.2 mm and 2.0 mm) in the 332 earthquakes observed at the Central Meteorological Observatory.



x - Maximum amplitude (double) of motion in mm.

y - Number of earthquakes whose max. amplitude of motion was **x**.

Different localities seem to have, in many cases, some prevailing directions of the earthquake motion. Thus, in Tōkyō, the principal directions are E-W and SE-NW [as will be seen from fig. 26 which shows the relative frequency of the different directions of motion of 431 earthquakes observed at the Central Meteorological Observatory during the 13 years between 1885 and 1897.]¹⁾

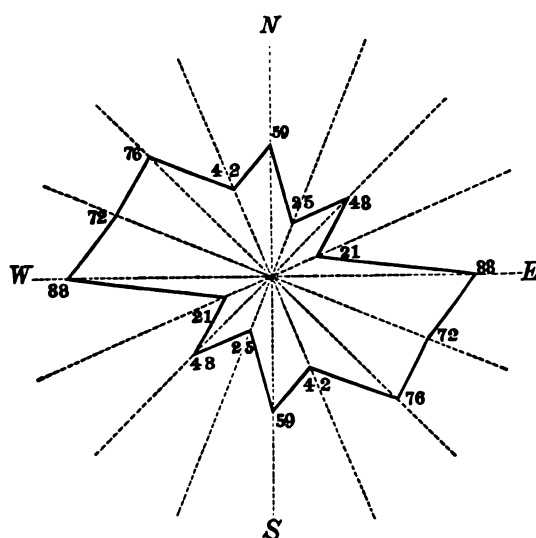


Fig. 26. The Directions of Earthquakes in Tōkyō.

Again, in Miyako, which is situated on the north-eastern coast of the Main Island, the motion in the E-W component is generally much greater than that in the N-S; the direction of the maximum vibrations in the different earthquakes being mostly E-W, ESE-WNW, and ENE-WSW.²⁾

This should be taken into account in choosing the direction of a long building, and in many other ways in practice.

Duration.

53. *The total duration of an earthquake depends on its*

1) F. Omori: On Earthquake Motions; E. I. C. Hō., No. 41.

2) F. Omori and K. Hirata: Earthquake Measurements at Miyako; Jour. Sc. Coll., Vol. XI.

magnitude and on the distance of the observing station from the origin. The relative lengths of the total earthquake duration and of those of the preliminary tremors and the main part will be best seen from the following results deduced from the earthquake measurements at Miyako:¹⁾—(a) Total earthquake duration varied between $8\frac{1}{2}$ and 200 sec., the average value being 72 sec.; (b) the duration of the preliminary tremors varied between 0 and 26 sec., the average value being $9\frac{1}{2}$ sec.; (c) finally the duration of the main part varied between 0.7 and 26 sec., the average value being 10 sec.

51. *The duration of the preliminary tremors does not depend on the magnitude of the earthquake but is found to vary with the distance.*²⁾ Thus if y denote the duration of the preliminary tremors of an earthquake at a place, whose distance from the origin of disturbance is x , we have the following empirical equation:—

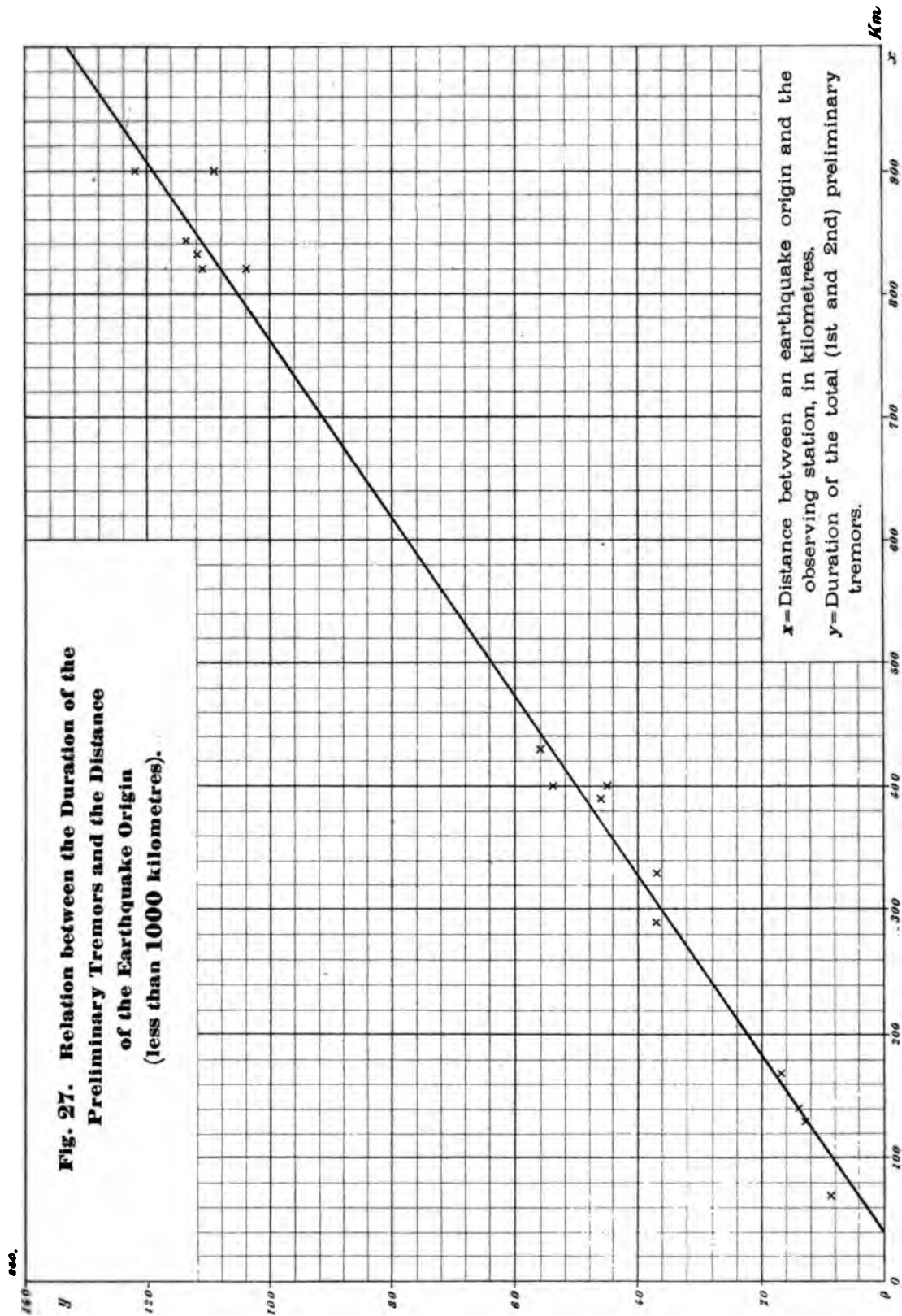
$$x^{\text{km}} = 7.27 y^{\text{sec}} + 38^{\text{km}}$$

which is to be used for values of x between 100 and 1000 km. [See fig. 27]. This equation is very useful and enables us to estimate, from the diagram at any station by a sufficiently sensitive seismograph, the distance of the origin of a shock. Or, if the seismographic records be simultaneously taken at two or more stations, we can, from the comparison of the durations of the preliminary tremors, easily fix the approximate position of the origin.

53. As to the *duration of the main part in destructive and strong earthquakes*, the result deduced from an examination of

1) F. Omori and K. Hirata: Earthquake Measurements at Miyako; Jour. Sc. Coll., Vol. XI.

2) F. Omori: Note on the Preliminary Tremor of Earthquake Motion; Jour. Sc. Coll., Vol. XI; also E. I. C. Publ., Nos. 5 and 13.



the seismograms obtained in Tōkyō and other places of the Tōkyō earthquake of Oct. 15th, 1884 and twelve other destructive and strong disturbances is as follows:—The two longest were the great Mino-Owari earthquake, 28 sec., and the Riku-U earthquake of 1896, 26 sec.; two others were each 19 sec.; and the remaining nine varied between 4 and $9\frac{1}{2}$ sec.¹⁾

Period of Vibrations at Miyako.

56. As illustrative of the earthquake motion in a rocky district, we may take the results of observation at the meteorological station of Miyako, which is situated on a small promontary of palæozoic rocks, about 30 m. in height. The periods of vibrations observed at Miyako were as follows:

The period of the maximum horizontal motion varied between 0·53 and 1·7 seconds; *the corresponding period in the vertical motion* varied between 0·53 and 1·7 seconds; the vertical and the horizontal components having, in most cases, the same period.

With regard to the *ripples* the period, which was the same in all the three components varied between 0·04 and 0·12 second. It may be mentioned in this connection that the quickest ripples so far observed were in the case of one of the after-shocks of the great Mino-Owari earthquake registered at the temporary seismological station set up in the village of Mitlōri in the Neo-Valley, the most central part of the meizoseismal zone; the complete period being only about 0·02 second.

I may also remark here that the amplitude of the ripples is

1) F. Omori: On Earthquake Motions; E. I. C. Hō., No. 41.

sometimes quite large, the greatest value observed at Miyako being 7.4 mm.

Earthquake Measurements at Hitotsubashi and Hongō.

37. As examples of earthquake measurements in non-rocky districts, we may take those made at Hitotsubashi and Hongō (Seismological Institute), both in Tōkyō. At Hitotsubashi the ground is low and very soft, while at Hongō, it is high and of hard clay.

*The average values of the elements of earthquake motion at Hitotsubashi are as follows.*¹⁾

(a) *Horizontal Motion:*—

Duration=101 sec.

Maximum amplitude=0.70 mm.

Period of max. motion=0.77 sec.

Maximum acceleration=20.0 mm./sec.²

Average period=0.76 sec.

(b) *Vertical motion:*—

Duration=58 sec.

Maximum amplitude=0.22 mm.

Period of max. motion=0.54 sec.

Average period=0.53 sec.

Thus it seems that the mean value of the period of the maximum vibration, both in the horizontal and the vertical component, seems to be practically identical with that of the average period. The case might be somewhat different if we take only strong earthquakes. The horizontal motion lasts twice as long as the

1) F. Omori: *Macro-seismic Measurement in Tōkyō*, II; E. I. C. Publ., No. 11, p. 51.

vertical motion, while the maximum amplitude and period of the former are respectively about 3 and 1.4 times those of the latter.

The period of vibration (horizontal) has no relation at all to the distance of the origin or to the mean radius of the area of disturbance. The conclusion is that the period at Hitotsubashi is essentially characteristic of the locality itself. Such is probably also true of other districts, where the soil is very soft.

At Hitotsubashi ripples do not practically exist, the soil being apparently too soft to admit of the formation of vibrations of a very quick period.

58. *The average values of the duration and the maximum amplitude at Hongō are as follows:—¹⁾*

Duration of horizontal motion=96 sec.

Maximum horizontal amplitude=0.79 mm.

Duration of vertical motion=51 sec.

Maximum vertical amplitude=0.22 mm.

Thus at Hongō also the horizontal motion lasts twice as long as the vertical; the amplitude of the former being nearly $3\frac{1}{2}$ times that of the latter.

The period of vibrations is not so uniform as at Hitotsubashi, there existing evidently several different sets of waves. Thus, with respect to the maximum horizontal vibrations there are essentially four periods, whose mean values are 0.26, 0.60, 1.25, and 2.6 sec.; the one most frequently occurring being the 2nd one. These four periods are roughly in the ratios of 1:2:4:8. With respect to the mean period of vibrations, there are similarly four periods: 0.22, 0.57, 1.18, and 2.2 sec.

1) F. Omori: Macro-seismic Measurement in Tōkyō, II; E. I. C. Publ., No. 11, p. 53.

In vertical vibrations, we have four different periods of 0.23, 0.44, 0.63, and 0.91 sec. These four sets of periods are roughly in the ratios of 1:2:3:4.

With regard to the ripples, there are two different periods of 0.20 and 0.47 sec.; the former predominating.

It is to be observed that the two periods of the ripples are practically identical with the two shorter periods of the vertical motion. This seems to indicate that the ripples and the vertical vibrations belong, in some cases, to one and the same kind of waves, which is probably in a part of the character of surface waves.

***Comparison of Earthquake Movements on
different Soils, etc.***

59. *The difference in the earthquake movements according to the nature of the soil* is well exemplified in the results of the observations at the three stations mentioned above. The comparison of the results at Hitotsubashi and Hongō are especially valuable, as here we can compare the measurements of the same earthquakes at the two places.

Prof. Sekiya, who was the first to make investigations relative to the systematic earthquake measurements in Tōkyō,¹⁾ obtained many important results, one of which relates to the comparison of the earthquake motion at Hongō and Hitotsubashi. He found that in hard ground (Hongō) the motion was smaller, the period quicker, and the duration shorter, than in soft soil (Hitotsubashi); their ratios being 1 to 2, 1 to 1.3 and 1 to 1.5 respectively.

1) S. Sekiya: Earthquake Measurements of recent Years especially relating to Vertical Motion; Jour. Sc. Coll., Vol. II.

The result¹⁾ subsequently obtained by Prof. Omori from a comparison of measurements of identical earthquakes made simultaneously at Hitotsubashi and Hongō was nearly similar to that obtained by Prof. Sekiya; the mean results of the comparison²⁾ being that the duration at Hitotsubashi was 1.7 times longer than that at Hongō, the maximum motion and the period at the former greater than those at the latter respectively in the ratios of 1.9 and 1.4. Consequently the maximum acceleration at Hitotsubashi is 1.2 times greater than that at Hongō.

The above comparison relates to non-destructive earthquakes. In destructive earthquakes, the period of principal vibrations will not be very quick and consequently will not much differ at Hitotsubashi and Hongō.

60. Loose soft soil and hard compact ground considerably differ in their elastic qualities, but their specific gravities do not much differ from each other. Consequently it is to be expected that the earthquake movements in a loose soft soil will, in general, be slower in period and greater in amplitude than those in a hard compact ground or rocky district.

The dependence of the intensity of earthquake motion on the nature of soil is sometimes very strikingly shown. Thus; for example, on the occasion of the great Mino-Owari earthquake, the shock was very strong in the city of Hikone in the province of Omi, where several houses and temples were entirely overthrown; while on a neighbouring hill the shock was much weaker, even stones lanterns (Japanese lamp posts for gardens) not being overturned.

1) Omori: *Macroseismic Measurement in Tōkyō*; E. I. C. Publ., No. II; or Hō, No. 41.

2) These results being mean of different set of earthquakes from those in the preceding Arts. are not the same as would be derived from the above.

The effect of earthquake motion will similarly be felt very severely in a valley district, where loose soil is superposed on a hard formation.

61. *Semi-gravity waves.* In destructive earthquakes, the ground surface may, under certain circumstances, be thrown into a species of gravity waves of short wave-length, just in the same way as strong earthquakes cause waves in lakes and seas; the earthquake movements must then be accompanied by a considerable amount of tilting of the ground. This probably accounts for the statement often met with in narratives of earthquakes that the ground was thrown into wavy forms. Especially on the occasion of the Mino-Owari and Shōnai earthquakes of 1891 and 1894, several reliable observers reported having witnessed this phenomenon. Further, in the epicentral districts of these earthquakes, several cases were noticed, in which the surface of the ground was thrown into permanent curved forms. These disturbances, which usually took place on paddy fields or other soft marshy ground, were sometimes limited in area, while in others they consisted of a series of parallel ridges and depressions continuing for several hundred metres. In all the cases, however, the wave-length, that is, the distance between successive ridges or depressions, which in the case of those formed in paddy fields can easily be recognized on account of the ridges projecting out of water, was small and amounted to from 20 to 40 m. Now, as the ground showed these permanent wavy deformations after the earthquakes, we may reasonably suppose that wavy movements of the ground were executed during the earthquakes.¹⁾

62 *Comparison of the Earthquake Motion above*

1) F. Omori: On Seismic Instruments; Verh. d. 1. intern. Erdbeben Conferenz zu Strassburg, 1901.

and below the Ground Level. From a practical point of view, with reference to the building of houses, it is interesting to investigate the shaking in pits, or excavations which might be made for foundations. Such a measurement was first undertaken by Prof. Milne, who found that the motion in a pit 10 feet deep was, in one case, much smaller than on the surface.¹⁾ The experiments subsequently made by Professors Sekiya and Ōmori in a pit 18 feet deep, at Hongō, seem to show that in severe earthquakes there may be less destructive effects in deep pits than on the free surface.²⁾

63. *Marginal vibrations.* At the edge of a steep bank or slope, the motion is intensified on account of want of side support. To this phenomenon of "*Marginal Vibrations*" is due the formation of cracks along river banks and the occurrence (during earthquakes) of landslips from mountain sides.

To observe the effects of marginal vibrations, late Prof. Sekiya placed a seismograph at the steep edge of a hill in Tōkyō, 38 feet in height, and another similar instrument at its foot. The motions at these two levels were found to be in the mean ratio of 2 : 1.³⁾

Earthquake Sounds.

64. In many cases, a rumbling sound like that of a distant thunder, or a rushing sound like a blast of wind is heard just before, or simultaneously with, the arrival of the tremblings of the ground,

1) Milne: On a Seismic Survey made in Tōkyō in 1884 and 1885; Trans. Seis. Soc., Vol. X.

2) Sekiya and Omori: Comparison of Earthquake Measurements made in a Pit and on the Surface Ground; Jour. Sc. Coll., Vol. IV.

3) Sekiya: The Severe Japan Earthquake of the 15th of January, 1887; Trans. Seis. Soc., Vol. XI, p. 87.

when the origin of the disturbance is near to the observer. These sound phenomena seem to be of frequent occurrence in a rocky district, but very rare at places situated in plains, like Tōkyō. They have been attributed to various causes by different writers; among others, Prof. Knott thinks,¹⁾ that “they are to be traced to the rapid vertical vibrations of the ground, so rapid as to be inappreciable on our seismographs.” It seems very probable, that they are due to the ripples whose period is very short as already mentioned.

The subject requires further study.

*Seismic Triangulation.*²⁾

65. *The velocity of propagation of the ordinary earthquake waves* has been determined with a great accuracy by the E. I. C., which instituted in 1894, at the suggestion of Professors Sekiya and Omori, a system of seismic triangulation, consisting of four stations provided with exactly similar Ewing seismographs connected by a telegraphic wire. The distance between the four stations varied from 2.29 km. to 10.86 km., the four instruments being simultaneously started at the time of an earthquake, and time marks being sent through the wire every second by means of a chronometer. The velocity of propagation was determined by identifying certain particular well defined vibrations in the seismograms, and finding the time differences of their arrival at the different stations. The result, deduced by Dr. Imamura, who has been carrying on the observation since 1895, was

1) Knott: *Earthquakes and Earthquake Sounds*; Trans. Seism. Soc., Vol. XII.

2) F. Omori: *Preliminary Report on the Seismic Triangulation*; E. I. C. Hō., No. 21.

A. Imamura: *Seismic Triangulation in Tōkyō*; E. I. C. Publ., No. 7.

1

1

1000

1000

1000

$$V=3.28^{\text{km}}\pm 0.05^{\text{km}}.$$

V thus may be taken as 3.3 km. per second.

When the differences of times of arrival of the earthquake motion proceeding from a near origin at the different stations of the seismic triangulation are accurately determined, we can approximately calculate the depth of the focus; the position of the epicentre and the velocity of propagation ($=3.3$ km. per sec.) being known. In this way, the depths of the centres of the earthquakes on Nov. 30th, 1894 and July 25th, 1898, which were felt in Tōkyō with moderate intensity and whose origins were situated in Tōkyō Bay, were found to be about 60 and 40 km. respectively.

With respect to the velocity of propagation of earthquake waves, I shall have more to say when I come to the observation of the insensible motion.

The Severe Tōkyō Earthquake of June 20, 1894.

66. The earthquake of June 20th, 1894 was the most violent that has shaken Tōkyō since the well known great earthquake of 1855. No house was absolutely destroyed, but in the lower parts of Tōkyō many brick buildings received severe damage, and large number of chimneys was thrown down. The diagram of the earthquake was taken by a strong motion seismograph set up in the Seismological Institute, this being the first time that a clear instrumental record of a destructive earthquake has ever been taken [see fig. 28.] The elements of motion were as follows:—Maximum horizontal motion= 73 mm., direction S 70° W, Period= 1.8 sec., maximum acceleration= 444 mm. per sec. per sec. Maximum vertical motion= 10 mm. Prof. Omori remarks that “The character of the earthquake motion was very simple,

the preliminary tremors having been followed at once by the single maximum vibration, which was much larger than the rest of the motion. I believe the motion in the meizoseismal area of destructive earthquakes to be generally of this type, and not necessarily so complicated as at great distances from the origin. In the case of small ordinary earthquakes, there is no single prominent displacement, the motion consisting of a great number of vibrations of nearly equal amplitude."

(C) **Insensible or Micro-Seismic Motion.**

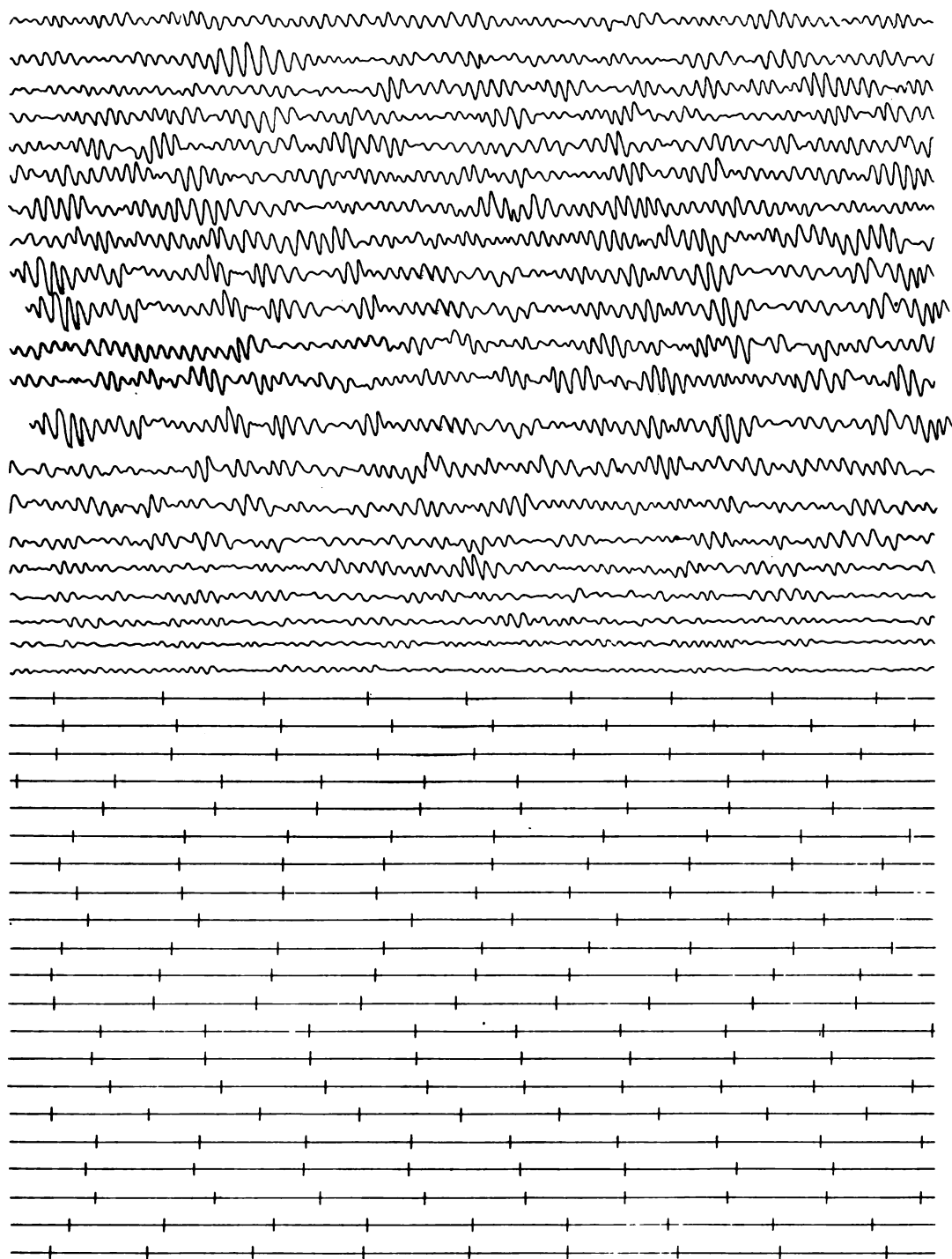
67. The insensible movements of the ground may be divided into two kinds, according as they are or are not of the earthquake origin. The vibrations not of the earthquake origin have been called Pulsatory Oscillations, while the others are those due to distant earthquakes (very distant and strong, or comparatively near and slight).

Pulsatory Oscillations.

68. The Pulsatory Oscillations are slow pulse-like movements of small amplitude [see fig. 29]. In some pronounced storms of pulsatory oscillations, the motion was quite as large as in small earthquakes; the maximum amplitude in each component being sometimes nearly 0.2 mm. Again, the horizontal motion is, in general, much greater than the vertical; although in some cases, the latter is very marked and nearly equal to the former.

1) Omori : Note on the Tōkyō Earthquake of June 20th, 1894 ; E. I. C. Publ., No. 4, p. 27.

Fig. 29. Part of the Diagram of Pulsatory Oscillation
Storm on Nov. 17th-18th, 1900.
(EW Component)
Multiplication 10 times.



Time: 1 tick-interval = 1 minute.



The wave-length of pulsatory oscillations seems to be much longer than those of the quick-period vibrations which constitute the ordinary seismic shocks.

The amplitude and period do not vary within a small area, such as Tōkyō. When considered, however, with respect to widely distant localities, there is a great difference in the frequency as well as the intensity of these movements. Thus in Tōkyō, Osaka, and Mizusawa, pulsatory oscillations occur very often and have not seldom quite a large amplitude, all these places being situated on plains of quaternary formation. On the other hand, the horizontal pendulum observations at Miyako meteorological station, Arima and Kyōto Imperial University show very few and slight traces of pulsatory oscillations. The three last named stations are situated on a small promontory of paleozoic formation among granite mountains, and in a valley surrounded by mountains.

As stated before, the period of pulsatory oscillations varies little, and remains generally constant for several successive hours, it may hence be supposed that these movements represent the proper vibrations of certain portions of the earth's crust, such for instance as the plain of Musashi in which Tōkyō is situated. In fact, there is no reason to suppose that the ground, when not disturbed by earthquakes, is perfectly at rest: on the contrary, it would be more general to assume that the different portions of the earth's crust are continually executing greater or less movements of some sort; and the periods of some of these vibrations ought to be determinable in each case from the geotectonic circumstances of the ground.

A careful examination of the horizontal pendulum diagrams obtained in Tōkyō shows that the pulsatory oscillations consist, in most cases, essentially of the vibrations with a period of about 4 sec., more or less mixed up with those of a period of about 8 sec.

The vibrations of 4 seconds period occur very frequently, but cases are not wanting, where the vibrations of the 8 seconds period predominate almost exclusively. Again there are sometimes cases, in which the two kinds of vibrations occur in different parts of one and the same diagram. Thus, in 41 out of the 46 cases of storms of pulsatory oscillations in 1900, the average period varied between 3.4 and 5.7 sec., giving a mean value of 4.4 sec. ($=Q_1$). In the remaining five cases, the average period varied between 7.1 and 9.3 sec., giving a mean value of 8.0 sec. ($=Q_2$): large pulsatory movements at the time of very deep cyclones having generally the 8 seconds period. Some of the cases, in which the period is between 4 and 8 seconds, are probably produced by the mixing together of the two series of movements. We may perhaps assume that the 8 seconds period vibration constitutes the fundamental oscillation proper to the Tōkyō plain, the 4 seconds period vibration being one of its harmonics.¹⁾

The period of pulsatory oscillations at Osaka¹⁾ varies between 3.1 and 6.9 sec.; the majority being between 4 and 5.9 sec. The total average value of the period comes out to be 5.1 sec., which is approximately equal to that most frequently occurring in Tōkyō, denoted by Q_1 above.²⁾

69. Pulsatory oscillations generally accompany low barometric pressure; the effect of a very deep cyclone being already sensible at a distance of some thousand kilometres. In a few cases, however, pronounced storms of pulsatory

1) F. Ōmori: Horizontal Pendulum Observation of Earthquakes at Hitotsubashi (Tōkyō), 1900; E. I. C. Publ., No. 13, pp. 81-86.

2) F. Ōmori: On Pulsatory Oscillations at Tōkyō and Osaka; Chishitsugaku Zasshi, No. 125, 1904.

oscillations occurred on days when very quiet weather prevailed all over Japan.

In Tōkyō, earthquakes rarely occur while pulsatory oscillations are going on actively. On the other hand, there are often local shocks when these oscillations come to a state of minimum activity. Prof. Omori, by observing the records of pulsatory oscillations, has been able, on several occasions, to predict the occurrence of an earthquake within some 10 or 12 hours.

Observation of Distant Earthquakes in Tōkyō.

70. From the observations made in Tōkyō of insensible motion due to distant earthquakes, made with Prof. Omori's Horizontal Pendulum Seismographs, many important results have been obtained, of which I proceed to give a very brief summary.

71. A careful examination of seismograms shows that the earthquake motion consists generally of several sections, in each of which the period remains essentially constant, while the amplitude is also on the whole constant, except for the occurrence of maximum and minimum groups.

The successive sections of the earthquake motion, illustrated in fig. 30, are as follows:—

The *1st Section*, in which we have vibrations of small amplitude and comparatively short period;

The *2nd Section*, having vibrations of somewhat larger amplitude, and often marked by the appearance of slow vibrations, superposed on the others;

The *3rd Section*, consisting of a few slow vibrations;

The *4th Section*, consisting of vibrations somewhat quicker than in the 3rd section, and of very large amplitude;

The *5th Section*, of vibrations of much shorter period than in the 3rd and 4th sections, and of large amplitude; followed by others of smaller amplitude, which may be called respectively

The *6th, 7th, 8th, &c. Sections*. The 3rd and following sections constitute the main part of the earthquake motion. And finally,

The *Tail*, being the feeble finishing part of the earthquake motion.

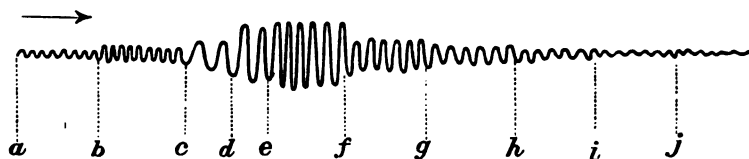


Fig. 30. *Diagrammatic Representation of the Earthquake Motion proceeding from a Distant Origin.*

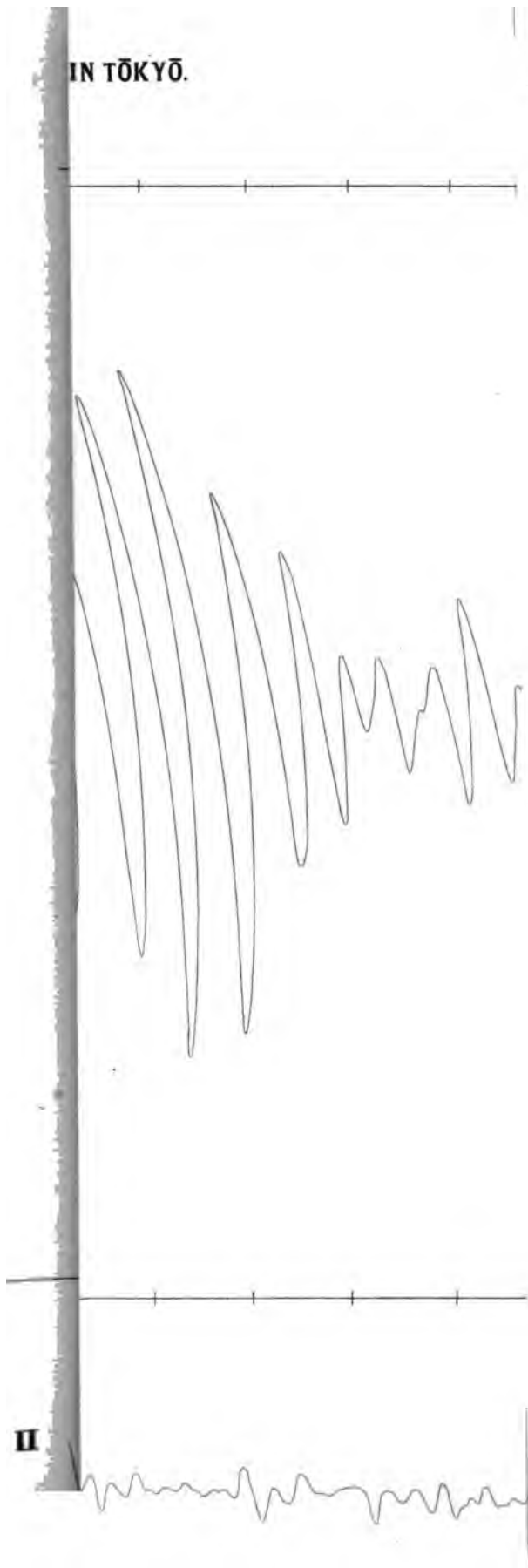
ab	1st Section, or 1st Preliminary Tremors.	
bc	2nd Section, or 2nd Preliminary Tremors.	
cd	3rd Section	Main Part, or { 1st Phase of the Principal Portion. 2nd " " " " " 3rd " " " " " 4th " " " " "
de	4th Section	
ef	5th Section	
fg	6th Section	
.....		
j	Tail, or End Portion.	

The 1st and 2nd sections are usually known as the *1st* and *2nd preliminary tremors*, the 3rd, 4th, 5th, &c. sections as the *1st, 2nd, 3rd, &c. phases of the principal portion*; and the tail as the *end portion*.

In earthquakes of near origin, the motion is, on account of the existence of quick sensible vibrations, much more complex than



IN TŌKYŌ.





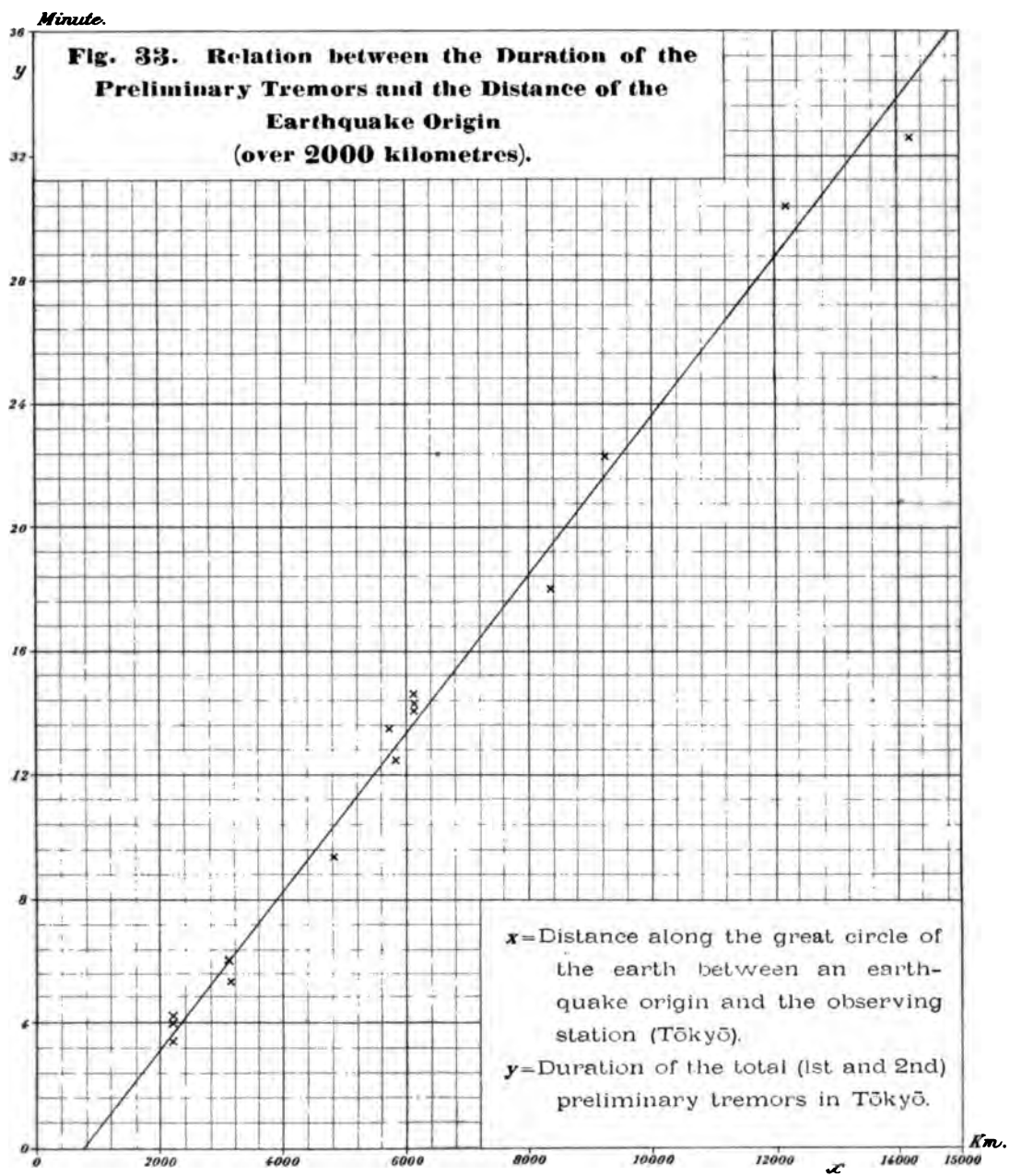
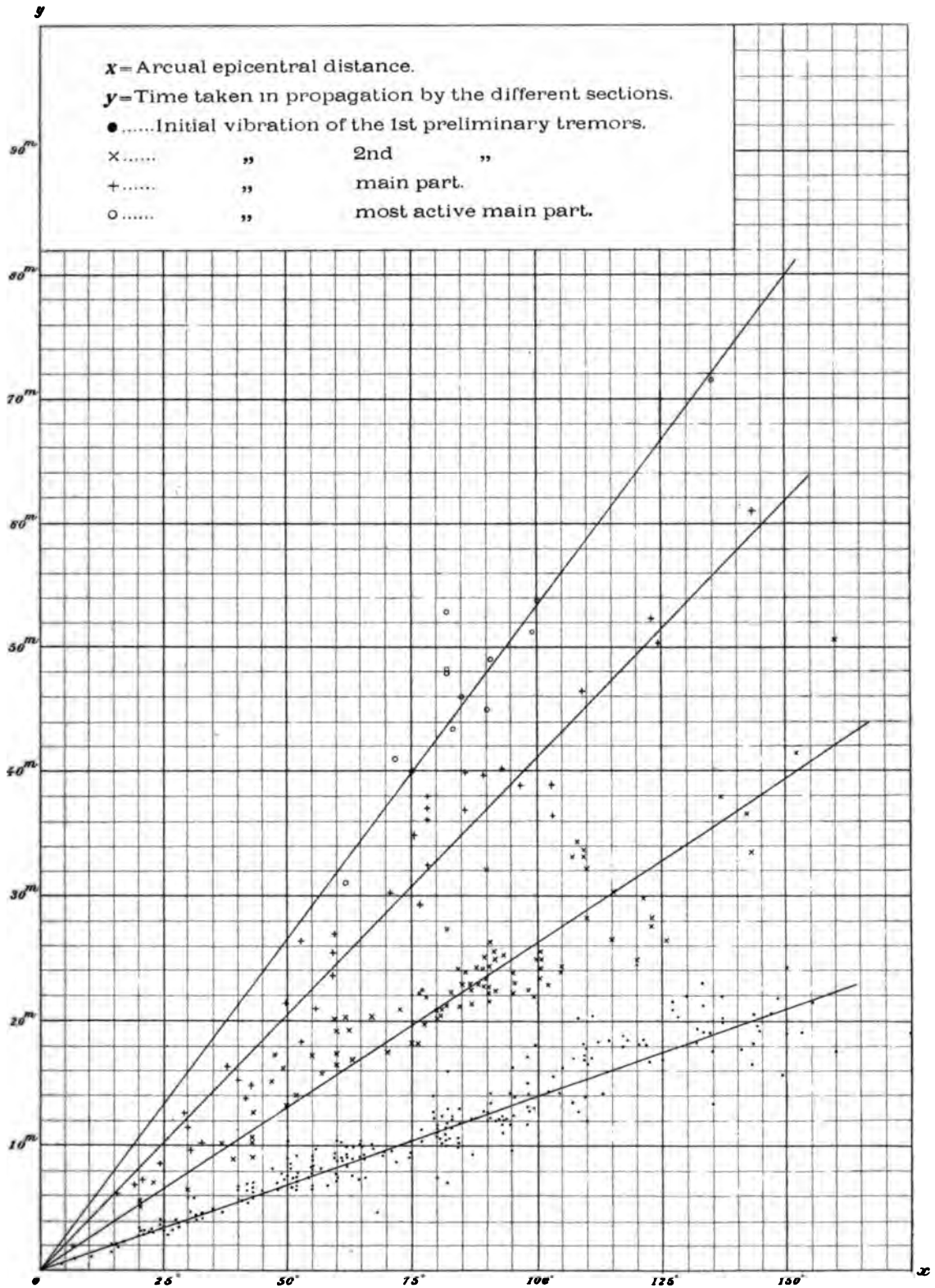


Fig. 34. Relation between Arcual Epicentral Distance and the Time taken in Propagation by the different Sections of the Earthquake Motion.



—

in distant earthquakes. I have already mentioned [Art. 49] that it may be divided into three sections, taking the records given by the ordinary seismographs: when seismograms taken with Omori seismographs are examined carefully, the existence of two stages of preliminary tremors may often be distinguished, but it is generally difficult to recognize different phases of the main part as in distant earthquakes; it is even possible, that the corresponding vibrations are included under different divisions.

Illustrative diagrams obtained with Omori seismographs are given in figs. 31, 32, and 37.

72. As in the case of near earthquakes, *the duration of the preliminary tremors* is found to depend entirely on the distance of the origin from the observing station: thus let x denote the arcual distance or the distance along the great circle between the epicentre and the observing station, and y the duration of the preliminary tremors, then from the observation of earthquakes whose x varied between 2000 and 14,000 km., the following equation between x and y has been deduced by Prof. Omori.¹⁾ [See fig. 33.]

$$x^{\text{km}} = 6.54 y^{\text{sec}} + 720^{\text{km}}$$

This equation is practically identical, for large values of x and y with the equation [of Art. 54] deduced from the earthquakes whose x is less than 1000 km. We have, then, the remarkable fact, that the duration of the preliminary tremors is proportional to the arcual distance of the origin. The time taken by each of the subsequent sections of the earthquake motion seems also to be proportional to the arcual distance.²⁾ [See fig. 34.]

(1903)

1) F. Omori: Horizontal Pendulum Observation of Earthquakes at Hitotsubashi (Tōkyō), 1909; E. I. C. Publ., No. 13, p. 87.

2) A. Imamura: On the Milne Horizontal Pendulum Diagrams obtained in Tōkyō; E. I. C. Publ., No. 16.

73. Periods of vibrations. The predominating periods in the different sections of the distant earthquake motion observed at Hitotsubashi (Tōkyō) were as follows; those very frequently occurring being given in black letters.

	sec.	sec.	sec.
1st preliminary tremors	1.04; 4.6 ; 8.7		
2nd „ „ „ „ „ „	8.5 ; 14.8		
3rd section... ..	22.9; 27.6		
4th „ „ „ „ „ „	13.6; 17.8; 22.3; 25.9		
5th „ „ „ „ „ „	9.3 ; 13.6		
Tail „ „ „ „ „ „	9.6 ; 16.0		

It will be observed that the two periods of about $4\frac{1}{2}$ and $8\frac{1}{2}$ sec. occur most frequently in the preliminary tremors; this being also the case with the observations made at Hongō.

The different periods of vibrations in the 1st and the 2nd preliminary tremors do not depend on their duration, that is to say, on the distance of the earthquake origin from the observing station. A similar conclusion probably holds good also for the periods in other stages of the earthquake motion.

74. Thus there are, in the 1st and 2nd preliminary tremors, two predominating periods, which may be denoted by P_1 and P_2 , and whose mean values are

$$P_1=4.6 \text{ sec.}, \quad P_2=8.3 \text{ sec.};$$

now these are practically identical respectively with the two periods, $Q_1=4.4$ sec. and $Q_2=8.0$ sec., found for the pulsatory oscillations in Tōkyō [Art. 68.] Moreover the periods P_1 and P_2 do not depend on the distance of an epicentre from the observing station, or on the nature of the disturbance at the seismic origin, but are characteristic of the region about Tōkyō.

We may hence probably explain the existence of the prelimi-

nary tremors somewhat as follows:—the waves of the preliminary tremors are transmitted along a deep layer of the earth's crust with a velocity of some 14 km. of which I shall speak presently, and communicate a sort of stress to the superincumbent surface layer of the earth's crust in the region about the observing station: the latter being, in consequence, thrown into its own proper vibrations. In fact, the preliminary tremors seem to be nothing else than the pulsatory oscillations, caused by the waves transmitted along a deep layer of the earth's crust from the origin of earthquakes.¹⁾

75. Taking the observations of 11 great distant earthquakes,²⁾ the predominating periods in the different sections of the motion are as follows:—

	sec.	sec.	sec.
1st preliminary tremors... ..	4.1;	7.8;	13.9
2nd „ „ „ „ „ „	4.8;	8.2;	15.0
3rd section	36.1		
4th „ „ „ „ „ „	27.5;	33.7	
5th „ „ „ „ „ „	20.4;	24.0	
6th „ „ „ „ „ „	11.7;	14.9	
7th „ „ „ „ „ „	14.3		
8th „ „ „ „ „ „	14.5		
Tail	9.9;	14.3;	19.8

The durations of the different sections of the earthquake motion are roughly equal to one another; the 3rd and the 4th sections being taken together.

The amplitude of motion is smallest in the 1st preliminary tremors, and greatest in the 4th and 5th sections.

The mean maximum (EW) amplitudes in the successive

1) F. Omori: Horizontal Pendulum Observations of Earthquakes at Hitotsubashi (Tōkyō), 1900; E. I. C. Publ., No. 13, p p. 84—86.

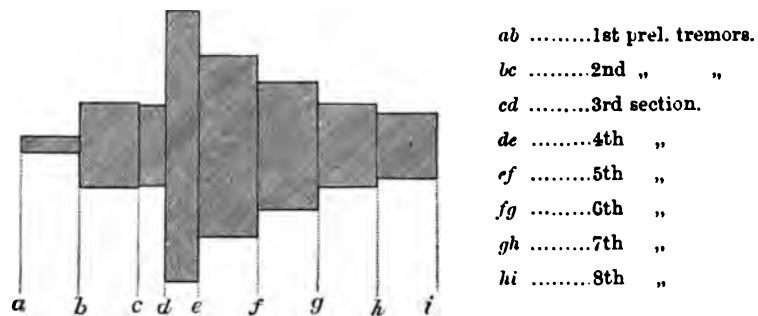
2) Loc. cit. p. 115.

sections of the earthquake motion, deduced from the observations of nine large disturbances, are as given in the following table, where 2a denotes the actual value, and 2a' the relative value, the amplitude of motion in the 1st preliminary tremors being taken as 100.

Sections of earthquake motion.	2a	2a'
1st preliminary tremors	^{mm.} 0.24	100
2nd ,, ,, ...	1.35	560
3rd section	1.32	550
4th ,, ...	4.36	1820
5th ,, ...	2.93	1220
6th ,, ...	2.02	840
7th ,, ...	1.35	560
8th ,, ...	1.03	430

Fig. 35 illustrates diagrammatically the character of motion in the first eight sections of great distant earthquakes, with regard to the duration and amplitude.

Fig. 35.



The Velocities of Propagation of the Vibrations.

76. In calculating the velocities of propagation of distant earthquake waves, it makes a great difference according as we suppose the waves to be propagated along the chord joining the origin to the observing station, or parallel to the surface. Recent investigations would seem to point to the latter as more probable. Calculated on this supposition, the velocities of the different corresponding waves of the earthquake motion come out practically the same, whatever the (arcual) distances; whereas on the chord supposition, the velocities of the corresponding waves come out quite different, according to the distances.¹⁾

If we denote by v_1 , v_2 , v_3 , and v_5 the velocities of propagation (supposed parallel to the surface) of the waves at the commencement of the 1st, 2nd, 3rd and 5th sections of the earthquake motion, which are usually well marked, their values deduced from the observations in Europe of the recent great Japan earthquakes are as follows:²⁾

$$v_1 = 14.1 \text{ km./sec.} \quad v_2 = 7.5 \text{ km./sec.} \quad v_3 = 4.7 \text{ km./sec.} \quad v_5 = 3.3 \text{ km./sec.}$$

The observation of the Caracas Earthquake of Oct. 29th, 1900, at Tōkyō and several European stations gave approximately the same results, viz. $v_1 = 13.6$, $v_2 = 7.2$, $v_5 = 3.4$ km. per second.³⁾

The values deduced by Dr. Imamura from a careful examination of the Milne Horizontal Pendulum Seismograms obtained at various stations all over the world are also similar to the above

1) Omori: Horizontal Pendulum Observ. of Earthquakes; E. I. C. Publ., No. 13.

2) Omori, loc. cit., p. 137.

3) Omori, loc. cit., p. 138.

values: viz. $\tau_1=13.2$, $\tau_2=6.8$, $\tau_3=4.5$, $\tau_4=3.3$, $\tau_5=2.8$, $\tau_7=2.4$, $\tau_8=2.1$ km. per second.¹⁾

77. The velocity of propagation of the vibrations at the commencement of the main part of a near earthquake was, as I have already stated [Art. 64], found by the method of Seismic Triangulation to be 3.3 km. per second, which is the same as τ_4 above. The velocity corresponding to the initial wave of the preliminary tremors of a near earthquake seems to differ very much according to the distance of the origin, but from the equation of duration of the initial vibrations and the distance of the origin [Art. 54], it must be tolerably great; two Formosan earthquakes and two Manila earthquakes gave a mean value of about 11 km. per sec. for this velocity. Quite recently, Dr. Imamura has found that even for earthquakes whose origin is distant less than 1000 km., by taking difference of times of arrival at two stations, which were some 300 km. distant, this velocity comes out to be about 13 km., which is approximately the same as τ_1 .²⁾ This, if true, is a further confirmation of the supposition of arcual propagation. An accurate determination of this velocity will, it is hoped, be undertaken in a near future.

78. Prof. Nagaoka's recent investigations³⁾ of the elastic constants of rocks, of which I shall speak presently, show that the approximate velocities of propagation of longitudinal elastic waves (calculated from the elastic constants of the specimens) varied from little over 1 km. to 7 km. per sec., by far the largest number having a velocity of about 3 km. This seems to show that the waves

1) Imamura: On Milne Horizontal Pendulum Seismograms obtained at Hongō, Tōkyō; E. I. C. Publ., No. 16, p. 115.

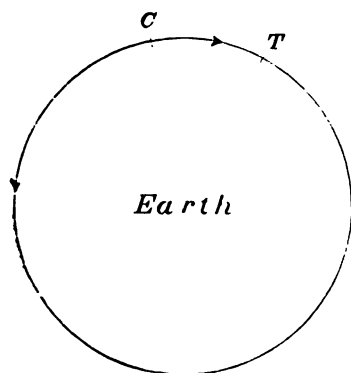
2) Imamura: Note on the Transit Velocity of the Earthquake motion originating at a near distance; Su. Butsu. K. G., Vol. II, No. 13.

3) Nagaoka: Elastic Constants of Rocks and the Velocity of Seismic Waves; E. I. C. Publ., No. 4, or Phil. Mag., May, 1900.

in the 5th section in distant earthquake motion and the principal waves in the near earthquake disturbance, both having a velocity of about 3.3 km. per sec. are propagated along the surface of the earth's crust. According to Prof. Nagaoka, older rocks have greater velocity than the new, and we shall have greater velocities as we go deeper down, until we come probably to a stratum of maximum velocity. It is probable, that the waves having velocity v_2 =say 7 km., and v_3 =say 4.5 km. are transmitted along a layer at some small depth within the earth's crust. For no rock tried, was there such high velocity as 13 or 14 km., but probably such velocity is attained by some tolerably deep stratum,—Prof. Nagaoka's "stratum of maximum velocity."

The above supposition gives a very easy explanation of the fact that the duration of the preliminary tremors is proportional to the arcual distance of the epicentre and the observing station, for this duration is the time between the arrivals of the initial waves of the preliminary tremors and of the main part, and therefore ought to be equal to the distance divided by the difference of velocities, $v_1 - v_3$, which is on our supposition found to be constant.

Fig. 36.



79. *Propagation of seismic waves completely round the earth.* Let T be the observing station (Tōkyō), and C the earthquake origin [fig. 36]. Then there are three sets of motion, which can be distinguished and which we shall denote respectively W_1 , W_2 , and W_3 .

waves¹⁾:—*firstly*, the W_1 waves are those propagated from C to T along the shortest path, parallel to the surface; *secondly*, the W_2 waves are those propagated from C in the opposite direction and arriving at T after passing through the antipode of C; and *thirdly*, the W_3 waves are the W_1 waves, which are propagated beyond T in the same direction, and again arrive at T after making one complete circuit of the earth. Fig. 37 which is the NS component diagram of the Turkestan earthquake of Aug. 22, 1902, recorded at Hongō, Tōkyō, indicates the W_2 and W_3 waves distinctly.

The identification of the W_3 waves is possible only in a very few number of cases; that of the W_2 waves is, however, more definite, being usually characterized by the fact that their period is much slower than those of the preceding vibrations, which form the tail of the W_1 waves.

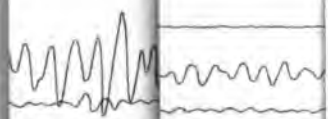
The average period of the W_2 waves is with a few exceptions very uniform and gives a mean value of 20.4 sec., which is identical with the predominating period in the 5th section; the period of the W_3 waves is also probably nearly the same as that of the W_2 waves. These facts seem to indicate that the W_2 and W_3 waves are the same waves as those which constitute the 5th section of the earthquake proper. That this is probably the case may easily be understood, as the vibrations in the 5th section have large amplitude, while their period is tolerably slow, but not so very long as that of the waves in the 3rd and the 4th sections.

The time interval between the arrival of the W_1 and that of the W_3 waves is $3^h 20^m 46^s$; this agrees with the time that would be taken by the vibrations in the 5th section in making one complete circuit round the earth, with the velocity of 3.3 km. per sec.

1) F. Omori: Horizontal Pendulum Observation of Earthquakes at Hitotsubashi (Tōkyō), 1900; E. I. C. I ubl., No. 13, p. 119.

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The amplitude of the W_2 waves is generally very much smaller than that of the W_1 waves; the motion of the W_2 waves being again much smaller than that of the W_1 waves. This ought of course to be the case, as the intensity of the seismic waves rapidly decreases with an increase of the distance from the centre of disturbance.

In a number of Milne horizontal pendulum photograms, Dr. Imamura has ascertained the repetition, in the W_2 waves, of the 3rd and 6th sections as well as the 5th section.¹⁾

80. *Longitudinal and Transverse Vibrations.* In the meizoseismal area of great destructive earthquakes, the directions of the maximum motion at different places generally converge to, or are symmetrical about, the epifocal region. Again, it is well known that the macro-seismic motion at great distance from the origin consists mainly of horizontal vibrations. These facts seem to show that the most active part of the earthquake motion consists of longitudinal waves; and we may suppose, therefore, that the velocity of propagation of the most active part in the macro-seismic disturbances, and also of the 5th section in distant earthquakes, characterizes the longitudinal component of the seismic motion. We have, however, no reason to suppose that the transverse component is entirely wanting in the seismic disturbances. Only its amplitude would in most cases be smaller and its velocity of propagation less than in the longitudinal component. Now, according to the results obtained by Prof. Nagaoka,²⁾ the ratio of the longitudinal to the transverse velocity would be about 1.6: 1 for granite, and 1.5: 1 for andesite. One of the three velocities, v_6 , v_7 , and v_8 , possibly v_8 , may be that of the transverse waves; the ratio v_6/v_8 being 1.8: 1.³⁾

1) E. I. C. Publ., No. 16.

2) Nagaoka: Elastic Constants of Rocks and the Velocity of Seismic Waves; E. I. C. Publ., No. 4.

3) Omori: Horizontal Pendulum Observations of Earthquakes at Hitotsubashi (Tōkyō), 1900; E. I. C. Publ., p. 124.

From an examination of Milne Horizontal Pendulum photographs, Dr. Imamura says: "It (6th phase of the principal portion or 8th section) develops itself sometimes quite distinctly and is easily distinguished from the preceding stages.....The velocity comes out to be 2.1 km. per sec., so that the ratio $v_5:v_8$ is 1.5,.....'"¹⁾

(D) Nature of Earthquake Motion.

S1. The earthquake motion may be linear or tilting or both combined. The important question is: which is it? All the results of the earthquake measurements which I have given are based on the assumption that the earthquake motion or the motion recorded by the seismographs is linear and not tilting. I shall now state some of the principal grounds for this assumption.

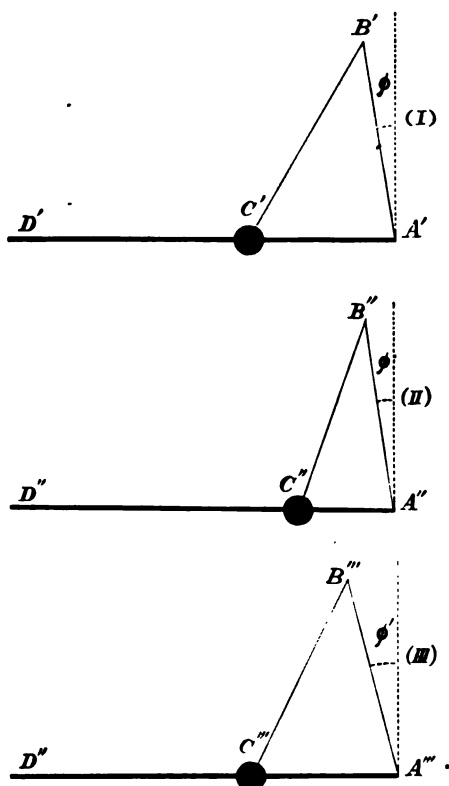
S2. *First, for the macro-seismic motion.* The length (λ), the period (T) and the propagation velocity (V) of a wave are connected with each other by the well known relation $\lambda = T \times V$, in which V is, say, equal to 3.3 km. per sec. To take an example, let us suppose that in an earthquake the vertical motion amounts to 100 mm.; the period T may be taken at $1\frac{1}{2}$ sec. the period of the principal vibrations in a strong earthquake being seldom less than 1 sec. The wave-length λ then comes out to be about 5 km., that is to say, there is a vertical displacement of 100 mm. in the horizontal distance of $2\frac{1}{2}$ km., the maximum angle of inclination of the ground surface being about $13''$. Such a small angle of inclination can not be felt by the ordinary macroseismic instruments, neither can it be directly observed with our eyes. The vertical motion of 100 mm. here supposed can occur only in an extremely destructive

1) Imamura: On Milne Horizontal Pendulum Seismograms obtained at Hongō, Tōkyō; E. I. C. Publ., No. 16.

earthquake; thus in the severe Tōkyō earthquake of June 20th, 1894, the vertical motion was only 11 mm. With small earthquake vibrations, whose period is short, the wave-length will be shorter than the value above estimated; but at the same time, the vertical motion is infinitesimally small and consequently the angle of inclination of the ground surface will be perfectly negligible.

Thus the earthquake waves, which constitute the macro-seismic motion and have a transit velocity of 3.3 km. per second, can, *in general*, have no sensible tilting motion. They are the

Fig. 38.



vibrations of the material forming the earth's crust, which for small earthquake movements, may well be supposed to lie within the elastic limit of the latter.

§3. The following is the principle of the experiments made to test the existence or non-existence of tilting in the macro-seismic motion, carried on since 1897 at the Seismological Institute.¹⁾ Let there be three horizontal pendulums, I, II, and III [fig. 38], in which C' , C'' , C''' are the heavy bobs; $B'C'$, $B''C''$, $B'''C'''$ the ties; $A'C'$, $A''C''$, $A'''C'''$ the struts; and $C'D'$, $C''D''$, $C'''D'''$ the writing pointers; the lengths

1) Omori : On the Nature of Earthquake Motion ; E. I. C. H5, No. 32.

$A'D'$, $A''D''$ and $A'''D'''$ being equal to one another ($=L$). Further, let the two pendulums, I and II, have a common angle ($=\varphi$) of inclination of the pendulum axis to the vertical, the ratios of multiplication $\frac{A'C'}{C'D'}$ and $\frac{A''C''}{C''D''}$ being unequal; while the two pendulums, I and III, have equal ratios of multiplication, $\frac{A'C'}{C'D'}$ and $\frac{A'''C'''}{C'''D'''}$, but unequal angles of inclination of the pendulum axes, φ and φ' . The three pendulums are placed with their planes parallel to one another. Thus the first two pendulums would have an equal sensibility for a tilting motion, but different magnifications for a horizontal motion; while the first and third pendulums have an equal magnification for a horizontal motion, but different sensibilities for a tilting motion.

The observations made with these contrivances of a number of small and also of moderately strong earthquakes show that the tilting motion is absent, or, if present, not large enough to be sensible to the ordinary seismographs.

§4. *Next, for Micro-seismic motion.*¹⁾ The observational ground for the assumed linearity of the long-period vibrations due to distant earthquakes is similar to that for the case of the macro-seismic motion, namely, the dependence of the recorded amplitude of motion on the multiplication ratio of the writing pointer, and not on the sensibility of the horizontal pendulum to tilting, in so far as the diagram is not confused by the proper oscillations of the heavy steady mass itself.

Another point, which bears on the question of the nature of the slow earthquake undulations, is the amount of the vertical acceleration which would exist according to the assumption that

1) F. Omori: Horizontal Pendulums for registering mechanically Earthquakes and other Movements; Jour. Sc. Coll., Vol. XI. Also: Results of the Horizontal Pendulum Observations of Earthquakes, July, 1898 to Dec., 1899. Tōkyō. E. I. C. Publ., No. 5.

these slow movements are due to the tilting of the ground. As illustrative examples we may take the Ceram earthquake of Sept. 30th, 1899, and the Alaska earthquake of Sept. 4th, 1899; the principal movements in these earthquakes observed in Tōkyō being respectively as follows:—recorded motion=54 mm., period=38 sec.; recorded motion=48 mm, period=16.2 sec. These vibrations, if due to the tilting of the ground, would correspond respectively to the following maximum vertical displacements and accelerations:—

Ceram earthquake:—maximum vertical displacement=1610 mm;

maximum vertical acceleration = 22 mm./sec.^2

Alaska earthquake:—maximum vertical displacement=416 mm;

maximum vertical acceleration = 31 mm./sec.^2

Again, in the Indian earthquake of June 12th, 1897, the period of large vibrations and the maximum inclination in Europe were, according to Dr. Agamennone, respectively 20 sec. and 12''. These quantities would correspond to a vertical displacement of 1220 mm. and the maximum vertical acceleration of 60 mm. per sec. per sec. Thus, under the supposition of tilting, the vertical displacement must reach often a considerable amount, the maximum acceleration varying, in the examples given above, between 22 and 60 mm. per sec. per sec. Movements like these would be sufficiently intense to be felt by us, and indeed a motion with an acceleration of 50 to 60 mm. per sec. per sec. may be classed as a *strong* earthquake shock. On the other hand, the maximum acceleration of the slow earthquake vibrations, calculated under the supposition of the horizontal motion, is found to be very small, being a mere fraction of one mm. per sec. per sec., an amount much too small to be sensible, or even to be registered by ordinary seismographs. Thus the conclusion is that the slow

earthquake vibrations can not, at least generally, be regarded as tilting motion.

85. *Pulsatory Oscillations.* The pulsatory oscillations seem also to be linear, the recorded amplitude depending simply on the multiplication ratios of the writing pointers of the seismographs.¹⁾

86. What has been said relates to ordinary and insensible earthquake vibrations and pulsatory oscillations. In very violent earthquakes, however, waves of short length, which are accompanied by a considerable amount of tilting, may be produced in soft grounds [as stated above in Art. 61]. Again, the ground seems to be subject to diurnal and other periodic changes of level from meteorological and other causes. These changes, the observation of which has not yet been carried on very satisfactorily, form an important subject of investigation in connection with the rigidity of the earth's crust.

87. I have briefly sketched the more important conclusions deduced from the observations, made mostly with Ewing-Gray-Milne and Omori seismographs; the latter is set up at present only in the Seism. Institute (both at Hongō and Hitotsubashi), the Central Meteorological Observatory, Kyōto Imp. Univ., International Latitude Observatory at Mizusawa, and quite recently at a few local meteorol. stations, such as Osaka, Kōbe, Tadotsu, Miyako, Ishinomaki, and several in Formosa and Pescadores; it is hoped to increase the number of such stations. With regard to the results stated both in this chapter and in the preceding one, future observations may cause some of them to be modified, indeed there are several points, on which a revision of the results obtained with the Ewing-Gray-Milne seismographs seem desirable, as I have

1) Omori: Horizontal Pendulum for registering mechanically Earthquakes, etc.; Jour. Sc. Coll., Vol. XI.

pointed out. Again I think it quite likely for instance, that the amplitude of slow vibrations recorded by any of the present instruments may be smaller than it really is, owing to the friction between the parts of the instrument. Other results will probably have details filled in.

In fact, the results obtained so far are mostly to be regarded rather as first approximations, and we are now entering upon the era of second approximations.

CHAPTER IV. GEOLOGICAL INVESTIGATIONS.

88. *The seismological character of a country* manifestly depends upon *its geological structure*; hence a thorough knowledge of the latter is essential to the proper understanding of the cause of earthquakes, of their distribution in time and space, of their frequency, and of many other things connected with earthquakes proper and other motions of the earth. Fortunately, the Imperial Geological Survey of Japan was organized in 1879, at the suggestion of Prof. E. Naumann of Tōkyō Univ. The excellent work, that the Survey has been and is doing, may be seen from the little pamphlet published by it for this Exposition with a catalogue of its exhibits; from this it will be seen that the reconnaissance survey of the country has been completed, except in the extreme south, and maps, both topographical and geological, published. The Survey publishes, besides maps, Explanatory Texts, Bulletins and Reports, mostly in Japanese.

89. *The Vulcanological Survey of Japan.* The E. I. C. began a detailed study of the new and old volcanoes of Japan as regards their internal structures, their rocks, their foundations and their modes of distribution, at the suggestion and under the direction of Prof. B. Kotô, who says: "In doing so, I can possibly get an insight into the structure of the land; and finally, I may be able to construct the geotectonic map, by means of which we could possibly know the condition underground, and the causes of the regional shaking and local points of earthquakes." *This*

1) Kotô: The Scope of the Vulcanological Survey of Japan; E. I. C. Publ., No. 3.

systematic vulcanological survey is, I believe, the only thing of this nature at present. The volcanoes already surveyed are the Myōkō, the Yoneyama, the Kenashi, the Ōshima (in Izu), the Haruna and Tsunootoshi, the Hakone and Atami, the Volcanoes of Izu Peninsula, the Akagi, the Arafune, the Yatsugadake, the Fuji and Aitaka, the Nikkō group, the Takahara, the Aso, the Nasu, the Niijima (in Izu), and the Iwate; the reports of these surveys, published with maps, in the Hōkoku of the E. I. C. have been already found of use in many ways. In this connection, I should mention Prof. Milne's account of the Volcanoes of Japan, in Vol. IX of the Trans. Seism. Soc.

90. Geologists from Tōkyō Univ., the Geol. Survey and the E. I. C. have not failed to visit scenes of severe earthquakes, volcanic eruptions, tsunamis, subterranean sounds, &c., to inspect the geological side of the phenomena, and their reports in various publications form valuable materials for the further study of the subject. I ought to mention specially Prof. Kotō's epoch-making account of the "Great Fault of Neo" in Central Japan.¹⁾ His account of the Shōnai earthquake of 1894 describing the geology of the district shaken and the fault to which he attributes that earthquake²⁾; and that by Dr. N. Yamazaki of the Riku-U earthquake of 1896³⁾ are also noteworthy as throwing light upon the discussion about the cause of earthquakes. The account of the Eruption of Bandaisan, June, 1888, by Prof. Sekiya and Assistant Prof. Kikuchi deserves also to be mentioned.⁴⁾ [For others see the contents of the reports of the E. I. C., in the Appendix.]

1) Kotō: On the Cause of the Great Earthquake in Central Japan, 1891. Journ. Sc. Coll., Vol. V.

2) E. I. C. Hō, No. 8.

3) E. I. C. Hō, No. 11, or Petermanns geogr. Mitt, 1900; Heft XI.

4) Sekiya and Kikuchi: On the Eruption of Bandaisan. Jour. Sc. Coll., Vol. III.

91. As to the causes of earthquakes in general, many theories have been put forward, which it would be out of the scope of the present address to discuss, even if I were competent to do so. It may however be remarked that almost all recent earthquakes in Japan, extending over a large area seem to be "tectonic", i. e., due to mountain-forming agencies, while in earthquakes accompanying volcanic eruptions, the shaking is confined to a comparatively small area.

CHAPTER V. PHYSICAL INVESTIGATIONS.

92. Earthquakes being due to the strain in the earth's crust, being in fact a violent relief of the stresses causing this strain, which has passed a certain limit, it is reasonable to assume that there would be some relation between earthquakes and physical phenomena which affect or are affected by the strain in the earth's crust. Hence the prime importance of examining the geological structure of the land; hence the reason to believe that the periodicity relations I have mentioned [Chapter II] are not accidental, but are based upon some causal relations; hence the significance of the observation of pulsatory oscillations, as probably indicating changes in the stresses; hence also the presumption in favor of making careful observations of such phenomena, as the Earth Magnetism, Variation of Latitude, Gravity, Changes in underground Temperature, &c., extended, if necessary, over large area and long period. By such observations, taken singly or conjointly, we may at last be enabled to find out some means of predicting the occurrence of an earthquake: we would at least leave nothing untried, as far as our means will allow, that was at all likely to help us in this ultimate object of the Committee. Of the scientific value of such investigations apart from seismological considerations, it is not necessary for me to speak here. Although we have not as yet succeeded in establishing such definite relations as to enable us to make a distinct prediction of an earthquake, (nor was it to be expected that we should arrive at such great result in so short a time with

so limited means.) yet the results in some of them at least are such as to encourage us to be patient and continue our investigations. I proceed to give a brief account of some of the work done in this line.

Earth Magnetism.

93. With regard to the Earth magnetism, disturbances have been observed in magnetometers at the time of earthquakes, but no systematic observations have been made with the object of ascertaining if there was any real relation between the two. The E. I. C. therefore decided to undertake this investigation: previously to this, observations had been made at the Central Meteorological Observatory in Tōkyō, since February, 1888, with Mascart's Magnetograph; the E. I. C. then initiated observations with similar instruments in Nagoya and Sendai in Sept., 1893; in Nemuro in Oct., 1896; and in Kumamoto, in Sept., 1898. In 1901, the Nagoya set was removed to Kyōto, chiefly in consequence of an electric railway passing too near the station. We thus have now *continuous magnetic observations at five places* distributed over Japan as evenly as circumstances allow. The photographic records are examined, and the results published periodically by the Central Meteorological Observ.

Systematic comparison with earthquake observations is being carried on, although, I am sorry to say, nothing has been published since 1897.

94. On several occasions, magnetic disturbances seem to have preceded or accompanied earthquakes:

Towards the end of 1893, on several occasions, the horizontal components at Nagoya station was disturbed for several days con-

tinuously, being followed after an interval of quiet of a day or two, by an earthquake; notably there was a disturbance lasting from Dec. 14 to Jan. 3, 1894, followed by a disturbance in declination and intensity (which was also observed at Tōkyō and Sendai) continuing up to 7th; three days afterwards there was a severe earthquake.¹⁾

For about a week before the severe earthquake in Shōnai district of Oct. 22, 1894, there was a magnetic disturbance recorded at Sendai; also to a smaller degree in Tōkyō, and in a still smaller degree in Nagoya.²⁾

For about four days before the great seismic “ tsunami ” along the north-eastern coast of June. 15, 1896, a disturbance in the horizontal component and declination was recorded at Sendai, and in a smaller degree at Tōkyō, but not at all at Nagoya.³⁾

Preceding the severe earthquake in Ugo and Rikuchū of 1896, magnetic disturbances were recorded in Sendai, Tōkyō and Nagoya, from midnight of the 29th to about 10 p. m. of 30th, the earthquake taking place about 1. 30 a. m. of 31st.⁴⁾

From 5th to 6th of May, 1900, disturbances were observed in all the five stations, and on 12th, at 2. 20 a. m., a tolerably severe earthquake shook the Rikuzen district.⁵⁾

These records will require careful examination and extensive comparison with magnetic observations abroad, as well as records of earthquakes and pulsatory oscillations, before we can consider any relation established between these phenomena.⁶⁾ In some few

1) E. I. C. Hō., No. 2, pp. 141-144.

2) E. I. C. Hō., No. 11, p. 35.

3) E. I. C. Hō., No. 11, p. 35.

4) E. I. C. Hō., No. 11, p. 106.

5) E. I. C. Hō., No. 32, p. 127.

6) See also Dr. Honma's discussion of the Records from Jan. 1896 to Aug., 1896., in E. I. C. Hō., No. 32, pp. 131-144.

instances where the disturbances seemed to be of limited extent, their vertical variations were calculated by the method given in Jour. Sc. Coll., Vol. XIV, § 12, from the sign of which the question whether the source of disturbance is above or below the earth's surface can be answered; the results are reserved from publication owing to the incompleteness of the magnetograph records. They however show that the depth or height of the source is small compared with the distances between the stations. Either three observatories in close proximity or six over Japan will be suitable for the kind of calculation there dealt with, the former giving immediately the differential coefficients of the disturbing forces with regard to the coordinates, and the latter giving quadratic expressions from which the differential coefficients may be calculated. It is at all events certain, that this investigation is one of the few means at present available for diagnosing the state of underground stress and a promising one, and it is desirable that it should be further developed.

I may mention here that at the request of the German government, the E. I. C. has made magnetic observations during the Antarctic Expedition of the "Gauss," in accordance with the program proposed.

95. Besides these continuous observations, the E. I. C. made a *Magnetic Survey of Japan*, during the years 1893-6, under the direction of Prof. A. Tanakadate. The survey had to be extended over so many years, owing to the fact that Prof. Tanakadate and other members of the survey could only be absent from their other duties during the summer vacations. Previously to this, there had been two surveys; one was made in 1882-3 by Messrs. Sekino and Kōdari, members of the staff of the Imperial Geological Survey, and the result was presented at the Interna-

tional Geological Congress at Berlin in 1885; it is published in a pamphlet by Dr. Naumann, entitled "Die Erscheinungen des Erdmagnetismus in ihrer Abhängigkeit vom Bau der Erdrinde" (Stuttgart, 1887). The other was made in 1887 by two parties respectively under Prof. Knott and Prof. Tanakadate; the result is given in the Jour. Sc. Coll., Vol. II, pp. 163-262. In Dec., 1891—Jan., 1892, a party under Professors Tanakadate and Nagaoka made a magnetic survey of the district about Gifu and Nagoya, to investigate the effect of so great a seismic event as the Mino-Owari earthquake was, on the magnetic elements of the country; an account of this survey is given in the Jour. Sc. Coll., Vol. V, pp. 149-192, showing that there has been a most remarkable change in the Isomagnetism of the district. How much of this was due to the same cause as the earthquake and how much to secular or other changes had to be investigated. This may be said to be one of the reasons, that induced the E. I. C. to undertake a general survey of Japan. The report of the last survey has just been published as Vol. XIV of the Jour. Sc. Coll. In it, Prof. Tanakadate says :

"The object of the survey was to get a closer view of the distribution of magnetic force in the country than hitherto has been done. It is hoped that we may obtain in this way some insight into the tectonic character of the country which might throw light upon the distribution of earthquake disturbances with regard to time and space.

"The object was twofold, first to obtain a general or normal, as it is sometimes called, distribution and second to get the extent and nature of local disturbances in special districts. With the first point in view a comparatively large number of stations were taken in places which were apparently free from distur-

“bances of any great magnitude; and with the second point in
“view observations were made in volcanic regions or in places
“where violent geological changes are supposed to have taken
“place. How near we have come to realize those expectations is
“clearly shown in the maps. It will be seen that we have done
“something toward the first, but for the second a much more
“extended series of observations are needed, although we believe
“that some of the prominent points are brought out by the
“present survey.”

Variation of Latitude.

96. As already stated, it is not unreasonable to suppose that there may be some relation between the seismic phenomena and the variation of latitude. The E. I. C. therefore on its organisation at once resolved to undertake the observations of latitude in Tōkyō: it took however some time before a Wanschaff's Zenith Telescope of 81 mm. aperture was procured, and the observations were only begun in July, 1895 by Dr. H. Kimura, at the Tōkyō Astronomical Obs., the reports of which are given in the E. I. C. Publ., Nos. 1 and 2. Subsequently, this work was transferred to the Geodetic Commission, at the same time that it was decided to establish the Observatory of the International Geodetic Association at Mizusawa.

The result of the examination of the mean monthly values of the latitude of Tōkyō (Astronomical Observatory) for nearly $8\frac{1}{2}$ years between Aug. 1895 and Dec. 1903, with reference to earthquakes in Japan, shows that all the destructive earthquakes occurred exactly or very nearly when the latitude was at a maximum or a minimum. The non-destructive extensive

earthquakes also indicate a similar tendency, though in a less marked degree. Small earthquakes seem, however, to have no particular relation to the latitude variation.¹⁾

With regard to the seismic periodicities, we have seen [Art. 12] that the epochs of the greatest activity of destructive earthquakes in Japan recurred on the average every $13\frac{1}{2}$ years, and [Art. 14] that the seismic activity at Kyōto presented a period of about $6\frac{1}{2}$ years. In this connection, it is interesting to note that, according to Dr. H. Kimura, who has studied the latitude variation during the interval between 1890 and 1902, the polar motion has a six years' period, the maximum deviations of the instantaneous pole having occurred in 1891 and 1897.

Gravity.

97. Measurements of gravity have been made in Tōkyō by several observers. Of these, the first was in 1878 by Professors Ayrton and Perry,²⁾ with a pendulum 9.3 metres long, giving the result $g=979.82$ cm./sec.² The next was in 1880 by Prof. T. C. Mendenhall³⁾ with a Borda's pendulum made by Salleron, giving $g=979.84$ cm./sec.² In 1883, Messrs. Smith and Pritchett⁴⁾ of the U. S. Coast and Geodetic Survey made observations with four pendulums, their results being $g=979.82$ cm./sec.² for pendulums No. 1—No. 3. and 980.0 for No. 4. The measurement made in

1) F. Omori: Note on the Relation between Earthquakes and Changes in Latitude; E. I. C. Publ., No. 18. For results in Europe, see Prof. Milne's report on Earthquake; and Changes in Latitude, Brit. Ass. for the Adv. of Sc., Rept. for 1900, p. 107; and Dr. A. Cancani: "Sopra un'ipotetica Relazione fra le Variazioni di latitudine e la frequenza dei terremoti mondiali." Bolletino della Soc. Sismologica Italiana, Vol. VIII. pp. 283-290.

2) Phil. Mag., April, 1880.

3) Memoirs of Sc. Dept., Tōkyō Univ., No. 5.

4) U. S. Coast and Geodetic Survey, Report, 1884.

1884 at Ogasawara-jima (Bonin Island, Latitude $27^{\circ} 4' 11''$ N) gave the value $g=979.47$.

98. The remarkable point to be noticed is that *all these values are greater than is to be expected at the corresponding latitude*. Was this due to some error in the measurements? Or was it real? The value of g is as a rule greater on islands than on the continent: was this the case here? If so, what did it signify? Did it indicate some peculiarity in the internal structure of these islands? As Prof. Nagaoka says: "In Ermangelung einer genauen Messung war es sehr wünschenswert die Beobachtung mit einem anderen feineren Instrumente zu wiederholen und die Frage aufzuklären, ob ein bedeutender Unterschied zwischen dem berechneten und dem beobachteten Wert wirklich bestehe. Nicht nur von der geodätischen und physicalischen Seite schien es höchst interessant für die Erdbebenforschung die Dicke der störenden Schicht auszurechnen, da diese Schicht offenbar mit der Häufigkeit der Erdbeben in unserem Land eng verknüpft sein wird."¹⁾ The E. I. C. therefore decided to make a more accurate determination of the value of g , than had been made hitherto, and the work was placed under the charge of Prof. Nagaoka. The Imperial Geodetic Commission having decided to make gravity determination a part of its work, the work together with the instruments already purchased was handed over to that Commission, Prof. Nagaoka remaining in charge as before. In 1899, absolute measurements were made in Kyōto, Kanazawa, Tōkyō and Mizusawa. The relative measurements connecting Tōkyō with Potsdam, and with other localities in Japan have since been going

1) Nagaoka, Shinjō and Ōtani: Absolute Messung der Schwerkraft in Kyōto, Kanazawa, Tōkyō und Mizusawa mit Reversionspendeln ausgeführt, Jour. Sc. Coll., Vol. XVI, Art. 11.

on; and the result has been published in the Comptes Rendus of the 14th meeting of the International Geodetic Association at Copenhagen in 1903. The value of g is 979.814 cm./sec.² (that of Potsdam beings 981.290) from which it appears that the difference between the calculated and observed values is within the limit of error of observation and presents no peculiarity. The observations¹⁾ made last year at five stations on the east coast of the Asiatic continent, viz. Singapore, Hongkong, Zikawei, Hankow and Shasi tend to confirm the result that gravity in Japan has a continental rather than insular character. From other observations, made with the same instruments, there are reasons to believe that in mountainous regions the force of gravity presents great anomalies. That these and future determinations of gravity at properly chosen spots will throw much valuable light upon the internal structure of the land, cannot be doubted.

Underground Temperature.

99. It was proposed to bore deep wells in properly chosen spots and to make measurements of temperature at different depths in these wells. We should thus get a knowledge of the distribution of temperature within the earth's crust, and if we can get a sufficient number of wells, of the *underground isothermals*, which will not only throw light upon the tectonic character of the land but also by their changes will indicate internal changes in stress, so that we may thus be able to predict an earthquake. A well was begun in the Tōkyō Univ. ground in Hongō, which reached a little

1) Shinjō, Ōtani and Yamakawa: On the Gravity and the Magnetic Survey at five stations in Eastern Asia; Abstract in Su Buts. K. G., Vol II.

over 400 metres in 1898; it was found advisable to stop at this depth, on account of the stratum met with. Reports of the boring operations and of geology of the well will be found in the E. I. C. Hō., Nos. 2 and 20. It has been found unfortunately impossible to continue boring in different localities at present, for want of funds, but the Committee has availed itself of wells which had been bored for other purposes, such as the supply of good water, or experimental boring for minerals. The first report by Prof. Tanakadate is in Hōkoku No. 45, containing measurements made in the Univ. ground well, in Yokohama, and in Fukushima, also measurements in Sasago and Kobotoke railway tunnels, the former of which is the longest in Japan, having a length of about fifteen thousand feet. The following is the result of measurement taken during 35 days, from April 27 to June 2, 1903, in the first mentioned well:

Depth below the top (metres)	Highest temperature during the period of observation.	Increase of temperature per 100 metres.	Depth for an in- crease of 1° C.
20.2	15.10 C		m
81.3	16.88	2.91 C	34.3
176.5	19.28	2.52	39.6
269.0	21.57	2.47	40.5
360.9	23.62	2.23	44.8

Seiches.

100. Under this head, I include not only the measurement of seiches in the ordinary acceptance of the term, viz. the periodic oscillations of the water of lakes, but also investigation into the existence of similar periodic oscillations in such bodies of water as bays, gulfs, straits, &c. I have already noticed

[Art. 30] Prof. Omori's discussion of the causes of "*tsunami*," and the examination of the records of tide-gauges, which seem to point to the existence of such movements. An account¹⁾ of the observations of seiches in Lakes Biwa and Hakone during the summer of 1901 will be found in the Su. Buts. K. G., Vol. I., No. 15. Observations have also been made in Osaka Bay and on the coasts of Tosa, Kii, Shimōsa and Rikuzen, with a *portable mercurial tide-gauge* specially devised by Dr. S. Nakamura,²⁾ which clearly point to the existence of seiche-like oscillations at these localities.³⁾ In the same number, is a very interesting article by Prof. Nagaoka on "*tsunami*," in which he extends Green's investigation to waves in a narrow and shallow channel of symmetrical section, and deduces an expression for the elevation of water, which will explain in a general way the nature and origin of "*tsunami*": he ascribes the frequency of "*tsunami*" along the eastern or Pacific coast of Japan to the presence of the Kuroshiwo or Japan Current; this current running nearly parallel to the coast he considers as forming an elastic boundary of a narrow band of water enclosed between the coast and itself, in which, as well as in bays and straits, periodic oscillations like the seiches of lakes exist. These being occasionally excited by local variations of atmospheric pressure, earthquakes, &c. give rise to high and destructive waves on account of the contour and shallowness of the shore. Further observations are necessary to the elucidation of this question, which may lead to important results, perhaps even to the prognostication of "*tsunami*."

1) In English. A French translation is given in Archives des Sciences physiques et naturelles, Genève, t. XV, pp 558-566; see also Zeitschrift für Instrumentenkunde, XXIII Jahrgang, Nov. 1903.

2) For a description of this instrument see Su Buts. K. G. Vol. I, No. 15, and also Zeitschrift für Instrumentenkunde (loc. cit).

3) The results have not yet been published.

Changes of the Level of Water in Wells.

101. Dr. S. Nakamura had observed periodic variation of the level of water in the well in the Univ. ground ; observations were subsequently made by Dr. K. Honda, with the instrument used in Seiches observations, and it was found that in general, there were two maxima and two minima in every 24 hours, the amplitude varying from 3 cm. to 1 cm. the phases coinciding with those of the tides in Tōkyō Bay; near full and new moons, the succession of the daily max. and min. is very regular, amplitude being decidedly greater than at quadrature; near quadrature, they occur just in the same phase as those of barometric changes; high barometer causes a lowering of the level, and vice versa; the rain does not seem to affect the level.¹⁾ Observations made at other wells have given approximately the same results.²⁾ These results showing variations in the underground pressure with tides and barometric pressure are specially important when taken in conjunction with the observations of Prof. Omori and Asst. Prof. Imamura as to earthquake frequency [Chapter II]. This investigation is to be regarded as a part of the study of the elastic tides in the earth's crust.

Two weak earthquakes occurred during the above measurements in Tōkyō, and it was found that the level curves were abnormally disturbed by zigzags which extended for 4 or 5 hours both before and after the earthquakes: this will require further investigation.

Determination of the Elastic Constants of Rocks.

102. This work was commenced in 1898 under the direction

1) Su Buts. K. G., Vol. II, No. 6.

2) Su Buts. K. G., Vol. II, No. 9.

of Prof. Nagaoka; I quote the following from his first report:¹⁾

“The vibration of the earth’s crust has from time to time been a favourite subject of discussion among the elasticians, and the propagation of seismic disturbance is a problem, whose solution has long been hoped for, both from the theoretical and the empirical point of view. With improved instruments, seismologists have recently determined the velocity of propagation with tolerable accuracy, but very little is known of the elastic nature of the medium through which the vibration has travelled. The resources from which physicists and seismologists draw their theoretical inferences are so scanty, that among the numerous rocks which constitute the earth’s crust, only a few of the most commonly occurring rocks have had their physical properties investigated. The questions of elasticity, having close bearing with the deformation of the earth’s crust, have repeatedly been a subject of research by several distinguished elasticians as Lord Kelvin, Boussinesq, Cerruti, and Chree. But we are baffled in our attempt to apply the result of subtle analysis to the actual problem, from the lack of our experimental knowledge as regards the elastic nature of the diverse rocks, which compose the outer coating of our planet. The present experiments were undertaken with a view to fill these gaps, and to supply on the one hand the wants of physicists, whose aim is to apply dynamics to the study of the geological phenomena, and on the other to meet the needs of seismologists, engaged in solving the problems touching the propagation of seismic waves.”

First experiments were made by Prof. Nagaoka to determine Young’s modulus and modulus of rigidity of about 100 specimens

1) Nagaoka: Elastic Constants of Rocks and the Velocity of Seismic Waves: E. I. C. Publ., No. 4. Also, Phil. Mag, 1920.

of ordinary Japanese rocks; it was found that they were not generally isotropic; archæan and palæozoic rocks could be cut into proper shape for experiment only in a certain direction as they were generally of schistose structure and extremely brittle in the direction perpendicular to it, there being naturally great difference in the elasticity in these directions; eruptive rocks were generally free from such directional behavior, but when subjected to continuous application of stress, the difference could be noticed. But as the directions of the axes of symmetry could not be determined simply, single moduli of elasticity and rigidity were determined for each specimen and the velocities of propagation of longitudinal and transverse elastic waves through it were calculated from these as if it were isotropic. These velocities range, for the longitudinal waves, from 7 km. to little over 1 km. per second, by far the largest number however having a velocity of about 3 km., which agrees very well with the observed velocity (3.3 km. per second) of the principal waves of an earthquake so that this may be taken to be the average velocity of propagation of a surface wave. [See Art. 77]. Such velocity as 14 km., which is that of the preliminary tremors, can be accounted for by supposing that as we go deeper into the earth's crust, the ratio of elastic constants to density increases: indeed the experiments seem to show that the elastic constants and the density increase with the age of the rocks, but the former more than the latter; and it is quite possible that *there may be a stratum of maximum velocity of propagation*. As Prof. Nagaoka points out, this hypothesis would give a very simple explanation of the fact that the duration of the preliminary tremors in the diagram of a distant earthquake is linearly proportional to the distance.



103. It was also found during these experiments that in some rocks Hooke's Law does not hold even for small flexure and torsion, the deviation being more marked in torsion than in flexure, and that there is a remarkable "hysteresis" in the relation of stress to strain. Special experiments were then made by Dr. Kusakabe under Prof. Nagaoka's direction to determine this.

For more than thirty specimens of different kinds of rocks, from archæan to quaternary, elastic constants were experimentally measured under different conditions. In both twisting and bending, couple and force respectively were made to change their values cyclically from positive to negative or *vice versa*, passing through zero continuously.

In almost every rock, not only no definite strain is associated with any given stress, but there is also no definite gradient in passing through a given state. That is to say, in the relation of stress to strain, rocks exhibit a marked hysteresis.

When its complete history is given, however, the amount of strain at any time under a given stress may be expressed by a formula, deduced from an empirical law of yielding, to sufficient approximation. General behavior of rocks may be studied by mere mathematical treatment of the above formula, the Hysteresis function.

As elastic constants, both moduli of rigidity and elasticity, generally increase from cainozoic to archæan rocks with great rapidity, the velocity of the seismic wave would increase with the ages of rocks through which the wave is propagated.

The amount of hysteresis decrease from the new rocks to the old ones. As a wave propagated through a

medium of great hysteresis fades more rapidly than that through one of less hysteresis, the seismic wave conductivity of rocks is least for caenozoic rocks and, increasing from mesozoic to palaeozoic rocks, it becomes many times greater for archæan rocks.

Elastic constants seem to be affected by temperature change. In ordinary temperature, elastic constants of sandstone diminish with rise of temperature. Both moduli of rigidity and elasticity are maximum at the temperature of about 9° C.

Discussions as to the relation between amplitude of seismic waves and velocity of propagation, and the relation between the hysteresis and after-shocks based on these experiments are also very interesting. Experiments will be continued with more specimens.¹⁾

It may be remarked here that experiments to determine heat conductivity of different rocks would likewise lead to important results, and it is hoped to make these experiments.

1) E. I. C. Publ., No. 14; Jour. Se. Coll. Vol. XIX, Art. 6; Su Buts. K. G., Vol. I, No. 14, and Vol. II, No. 11

CHAPTER VI. PRACTICAL.

104. One of the objects of the organization of the E. I. C. is, as already stated, to investigate what can be done to reduce the disastrous effects of earthquake shocks to a minimum by the choice of proper structure, materials, position, &c. For this it is necessary on the one hand to know the nature of the earthquake movements, &c., and therefore most of the investigations mentioned above have an important bearing on this question; on the other hand it is evidently important to know what effects strong earthquake shocks have produced and are likely to produce on existing structures and buildings. With this last end in view, the Committee has collected reports from experts, whenever there has been a destructive earthquake: it has also made many experiments on purpose to find out these effects.

Reports.

105. Among the valuable reports concerning destruction of buildings and engineering structures in the E. I. C. Hōkoku, I may mention the following:

Report on the damage to the Tōkaidō railway caused by the great Mino-Owari earthquake of 1891, and on the work of restoration, by Dr. K. Haraguchi, the chief government railway engineer. With 33 Sheets of maps and drawings. E. I. C. Hō, No. 1.

Reports by Dr. Emori, chief engineer of Aichi Prefecture, and Dr. T. Sayegi, government engineer, on the effects of the same earthquake in the prefectures of Aichi, Gifu and Miye. E. I. C. Hō, Nos. 2 and 3.

Report on the damage to buildings caused by the Hokkaidō earthquake of March 22, 1894, by Dr. K. Ishii, Asst. Prof. of Architecture in the Engineering Coll., Tōkyō Imp. Univ. E. I. C. Hō, No. 3.

Reports on the damage caused by the severe Tōkyō earthquake of June 20, 1894, communicated by Messrs. K. Tatsuno, T. Katayama, T. Sone, and T. Nakamura (E. I. C. Hō, No. 4, with 109 pls.); by Messrs. Tsukamoto, Noguchi and Yamazaki (communicated by Prof. Tatsuno and Prof. Nakamura, E. I. C. Hō, No. 7, with 28 pls.)

Reports on the damage caused by the Shōnai earthquake of 1894, by Prof. Omori (E. I. C. Hō, No. 3, with 23 pls.); by Prof. T. Nakamura, (ditto with sketches); by Dr. T. Sone (ditto with sketches); communicated by Prof. Tatsuno and Prof. Nakamura (E. I. C. Hō, No. 7, with 122 pls.); and by Dr. M. Noguchi (ditto, with 10 pls.).

Reports on damage to buildings caused by the great Riku-U earthquake of 1896, by Prof. Nakamura, and by Dr. Sone (both in E. I. C. Hō, No. 11).

Reports on buildings damaged by the great Indian earthquake of 1897, by Prof. T. Nakamura (E. I. C. Hō, No. 22, with 42 pls.); on the Engineering structures in Assam, damaged by the same earthquake, by Dr. T. Koyama (E. I. C. Hō, No. 25, with 41 pls.).

These reports have been very valuable not only to the Committee but to engineers, architects and builders in general, in showing the mistakes and defects to be avoided, and precautions to be taken against earthquake shocks. [I append here a few plates showing some of the effects of the earthquake shocks.]



Fig. 39. NAGOYA SPINNING MILL.

Showing the effects of the Mino-Owari Earthquake of 1891 on a Brick Building and on a Chimney.



Fig. 40. NAGOYA CASTLE.

Showing the slight effects of the Mino-Owari Earthquake of 1891.

1000



FIG. 41. NAGARAGAWA BRIDGE.
Showing the effects of the Mino-Owari Earthquake of 1891.

72.
Chm. 9/11



Fig. 42. BIWAJIMA.

A Suburb of Nagoya, showing the Destruction of Japanese Houses and a Railway Culvert, in the Mino-Owari Earthquake of 1891.





Fig. 43. Sakata Primary School.

Showing the shearing effect, and the projecting porch thrown down (Shōnai Earthquake of 1894).



Fig. 44. Yamagata Primary School.

Showing a large crack in the ground, the building uninjured (Shōnai Earthquake of 1894).



Fig. 45. A Temple in Sakata.

Showing the shearing effect, and the projecting part thrown down
(Shōnai Earthquake of 1894).



Fig. 46. A Rustic Bridge.

Damaged by the Shōnai Earthquake of 1894.

Experiments relative to Soil.

106. To this class belong the experiments already described, as to the relation of the soil and shocks [Arts. 59, 60]. Experiments with regard to vibrations in pits and cutting off or intercepting vibrations by means of trenches dug around a building [Art. 62]; marginal vibrations [Art. 63], &c., all have their applications in this connection.

Strength of Materials and Joints.

107. The E. I. C. was obliged to include the determination of the strength of materials, and of joints, among its work, as there has been no systematic work done in this most necessary line. The reports of various tests of timber from different parts of Japan will be found in the E. I. C. Hō, Nos. 2,3 and 35 (by Prof. B. Mano); Nos. 15 and 40 (by Prof. S. Tanabe). Experiments were also made with bricks jointed under different conditions with different mortars, the results of which are reported in the E. I. C. Hō, Nos. 10, 12 and 23 by Prof. S. Tanabe.¹⁾

The Earthquake-proof Brick Building.

108. This structure is built in the Tōkyō Univ. ground at Hongō, on a solid concrete foundation, and covers a square area of nearly 83 sq. metres. The walls are of parabolic section with vertex downwards [as shown in fig. 47]; 5.5 m. high, 2.4 m. thick at the ground level, 0.7 m. thick at the top. A tiled roof

1) Also in E. I. C. Publ., No. 3, pp. 33-33.

with skylights rests loosely on the walls; the entrance about 2.6×3.4 m. is the only opening in the walls. The walls were made of parabolic section, that being the section giving uniform strength throughout the height:¹⁾ the cements and mortars were carefully tested before being used; and the details of construction have been reported in the E. I. C. Hō, No. 1, for future reference. The object in building this structure, which was designed by Prof. K. Tatsuno, is to have an earthquake-proof building, that will stand any shock likely to occur in Tōkyō, and will serve as a sort of standard, with which to compare the effects of a shock on ordinary brick buildings: it is also very useful as a solid Seismological Observatory.

Movements during Earthquakes of Walls of Brick Buildings.

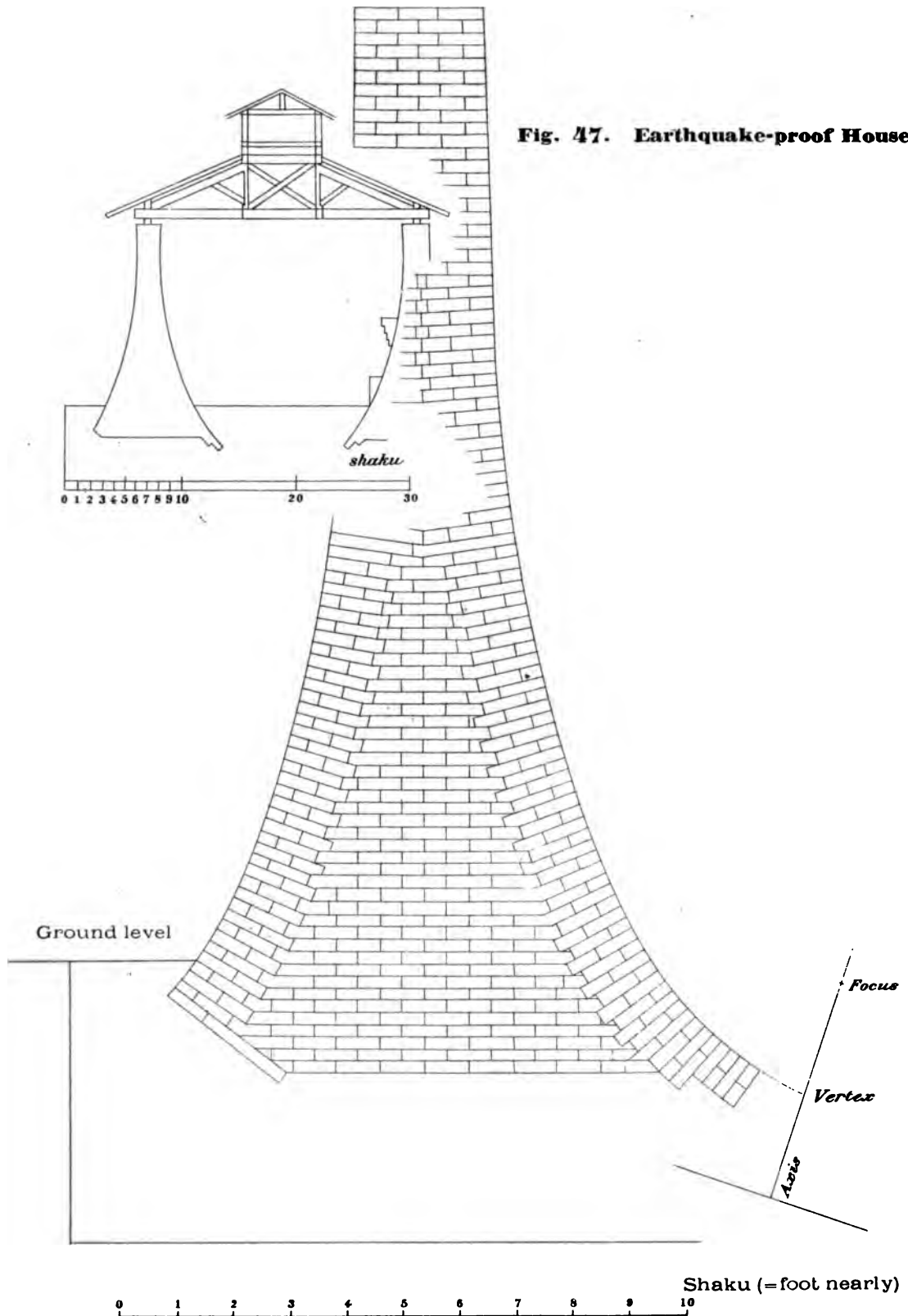
109. In 1883-1884, Prof. Milne made a series of highly interesting measurements with duplex pendulum seismographs of the movements produced by earthquakes in certain buildings in Tōkyō. For an account of his experiments, you are referred to Trans. Seis. Soc., Vol. XII.

As damage to brick buildings caused by an earthquake is generally due to the fracturing of their walls in consequence of strong horizontal motion, it is important to make earthquake measurements at different portions of the walls.

Between 1894 and 1898, Prof. Omori made measurements with Ewing's Horizontal Pendulum Seismographs of the earthquake motion of the external wall of the upper west corridor of the Engineering College of Tōkyō University, the instrument being fixed near the top of the wall at the middle of its length.

1) Omori: Seismic Experiments on the Fracturing and Overturning of Columns; E. I. C. Publ., No. 4, p. 107, or E. I. C. Hō, No. 28.

Fig. 47. Earthquake-proof House.



Comparing the diagrams so obtained with those obtained on the ground, it was found that, in the case of small earthquakes, which consisted of vibrations of comparatively slow period, that is, above 0.5 sec., the motion was practically equal in the upper story and on the ground surface. On the other hand, in earthquakes which consisted of quick-period vibrations, the motion at the top of the wall was greater than that of the ground surface in the average ratio of 2:1. As the period of vibration was the same for the two places of observation, it seems that in shocks of violent nature the wall, on which the roof rests, behaves like an inverted pendulum, its motion synchronizing with the earthquake motion. Practically, in destructive earthquakes, the damage of two-storied brick buildings is in general limited to the upper story. Thus it is not seldom that the walls of the lower story remain uninjured or only slightly cracked, even when the damage to the upper story is so severe that the walls are knocked down and roof falls in, evidently owing to the magnification of motion in the higher part of the walls.¹⁾ [See fig. 39.]

Another series of measurements related to the eastern end wall of the Natural History Museum, which is a two-storied brick building situated not far from the above. The total height of the wall was 53 feet; the seismograph having been attached to the wall at a height of 31 feet from the ground. The wall, which was evidently a weak one, was shaken considerably by earthquakes; the duration and amplitude of motion being nearly three times those at the ground surface. In this case, the period of vibration of the wall was practically constant, the mean value being 0.33 sec. This shows that the wall behaves in earthquakes like an elastic

1) E. I. C. Hō, No. 29, or E. I. C. Publ., No. 4, pp 7-11.

spring and executes vibrations with its own period, whatever the period and amplitude of the ground motion may be. However in cases of very slow vibrations, say of period longer than 2 seconds, the movements are felt equally on the ground and at the top of the wall.¹⁾

Finally, the earthquake motion measured at the 3rd story of the Mitsu-Bishi Bank, a brick building which is situated on the low ground of Tōkyō, did not differ from that at the basement.

The above examples will show that the movements of the walls of brick buildings produced by earthquakes differ very much according to the quality of the structure.

Wooden Houses.

110. In 1895, the Committee published a set of directions on the essential points to be observed in wooden house construction so as to make it better able to stand earthquake shocks. An English translation will be found in the E. I. C. Publ., No. 4, pp 1-5, (with 23 figs). The chief faults in ordinary Japanese wooden construction are the weakening of pillars by being very much cut into, and the want of cross ties and struts, so that very often the whole building suffers simple shearing [see figs. 43, 45,]. Some models, illustrative of the above mentioned essential points, were made, one of which was sent to Shōnai, the district damaged the year before. [I here give photographs of three of these models.²⁾]

Besides these small models, two wooden earthquake-proof houses were constructed, one in Nemuro, and one in Fukagawa, Tōkyō. Nemuro was chosen, because it was one of the most

1) Omori: Motion of a Brick Wall produced by Earthquakes; E. I. C. Publ., No. 12.

2) An account of these models is given in the E. I. C. Hō, No. 13.



Fig. 48. MODEL OF A FARMER'S COTTAGE.

Showing the essential points of construction recommended by the E. I. C.

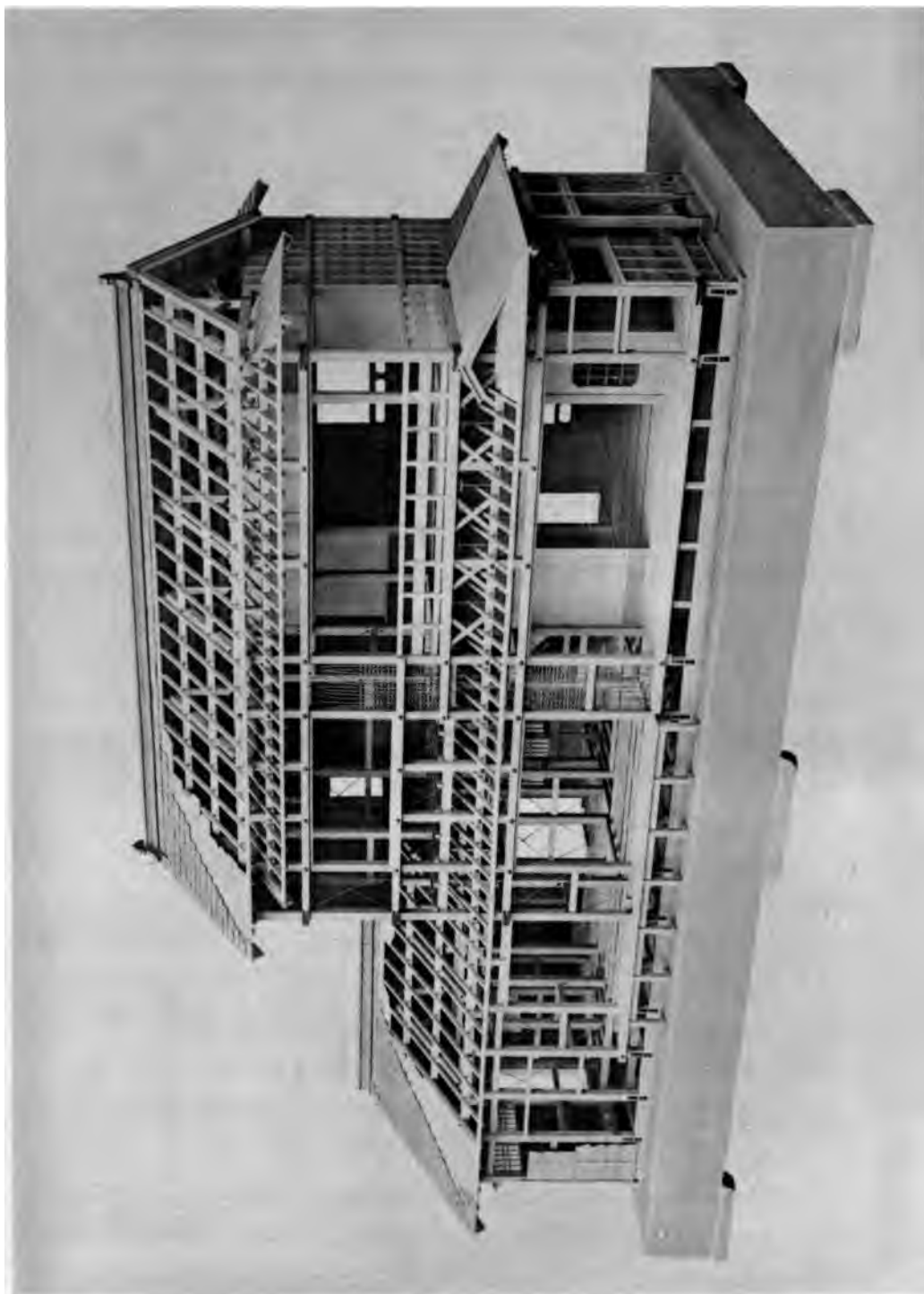


Fig. 49. MODEL OF AN ORDINARY DWELLING HOUSE.
Showing the essential points of construction recommended by the E. I. C.



Fig. 50. MODEL OF A PUBLIC BUILDING.
Showing the essential points of construction recommended by the E. I. C.

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shaken spots in the extreme north; Fukagawa was chosen on account of the soil there being of soft alluvial mud, so that it was likely to be well shaken; it serves as one of the stations of the Seismic triangulation [see Art. 64].¹⁾

Chimneys.

111. Much damage to chimneys, especially factory chimneys, having been caused by the great Mino-Owari earthquake of 1891, and Tōkyō earthquake of 1894, a great deal of attention was called to their construction. The E. I. C. made some suggestions directly after the Tōkyō earthquake, as to immediate steps to be taken in their repair and construction. Prof. Mano's reports on damage to factory chimneys in Ōsaka and Tōkyō caused by the destructive earthquakes of 1891 and 1894 [E. I. C. Hō., Nos. 5, 14.] are valuable contributions to this subject.²⁾ The members of the Committee have availed themselves of every opportunity to collect materials necessary for the scientific treatment of the subject. A few of the experiments made are reported in the Hōkoku and in the publications.³⁾ The chief object in these experiments was to find out the nature of their vibrations, for on that, of course, will depend the seismic stability of these structures.

The Shaking Table.

112. For the application of seismology to construction in

1)* For details of construction of these houses, see E. I. C. Hō., No. 13.

2) See also Omori, *Seismic Experiments on the Fracturing and Overturning of Columns*, E. I. C. Publ., No. 4, p. 117.

3) Omori: *Note on the Vibration of Chimneys*; E. I. C. Publ., No. 12, with 5 pls; Mano and Tanakadate: *Note on the Vibrations of a Chimney*; E. I. C. Hō., No. 21, with 9 pls.

earthquake countries, it is necessary, besides the observation of the damage due to actual earthquakes, to investigate experimentally the effects of artificially produced movements on various models of construction, the ultimate object being the calculation of the seismic stability of given structures and the finding out of the forms best suited to withstand earthquakes.

For this purpose artificial earthquake motion was produced by means of a *shaking table*, designed by Professors Mano and Inokuty, which consisted of a stout wooden floor properly mounted on strong supports, and which can be made to move with independent horizontal and vertical simple harmonic motions by means of steam engines.¹⁾ As the maximum ranges of motion of the table amounted to 150 mm. and 90 mm. respectively in the horizontal and vertical directions, and as the period can be made as small as 0.2 sec., movements much more destructive than those which took place at Nagoya or Gifu on the occasion of the great Mino-Owari earthquake can easily be produced.

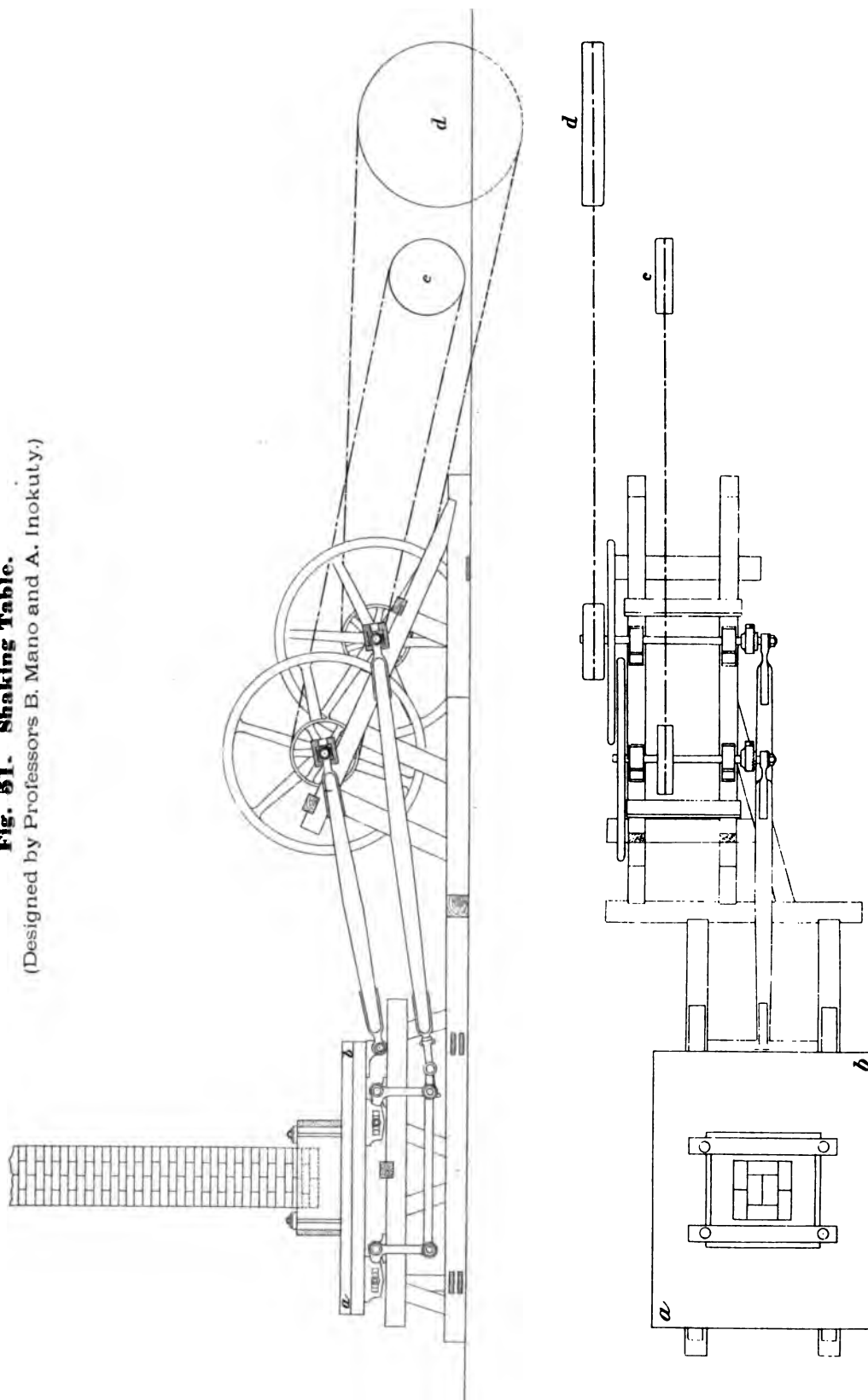
Some preliminary experiments were tried with small models of wooden structures made for the purpose, but soon it was found advisable to begin with simple elements of construction ; and also for the reasons stated in Art. 109 as well as for simplicity, motion was confined to the horizontal only.

Fracturing and Overturning of Columns.

113. In 1898-99, Prof. Omori made a series of experiments, fracturing some 24 brick columns and overturning numerous other columns, by placing them on the above table and

1) Mano : Appareil pour l'Étude théorique des Tremblements de Terre ; E. I. C. Publ., No. 3, pp. 85-86. Also see E. I. C. H5, Nos. 2 and 21.

Fig. 81. Shaking Table.
(Designed by Professors B. Mano and A. Inokuty.)



a b is the shaking table, which can be moved horizontally and vertically by means of the two steam engines **c** and **d**.



shaking them; the largest column had a height of 1810 mm. and a cross section of 233×233 mm. A second series of experiments was carried on in 1899-1901, in which about 80 solid and hollow brick columns were fractured; of these the largest was about 2 m. high and had a cross section of 48×46 cm. Other experiments on the sliding and overturning of numerous columns were also made. The results of the first series are given in the E. I. C. Publ., No. 4, pp. 69-141, or Hōkoku, No. 28; the full report of the second series has not yet appeared.¹⁾

The practical importance of the conclusions that may be deduced from these experiments will be at once evident, when we consider that they will apply approximately to bridge piers and chimneys: I can here only give a very brief outline of them.²⁾

114. *For fracturing experiments*, the brick columns were each firmly fixed to the shaking table at the base, its top being free. The fracturing process consisted in moving the table simple-harmonically within a certain range of motion. At first the motion of the table was slow, but it was gradually quickened till the period reached a certain value; when the acceleration of motion became sufficiently great, and fracture of the column took place generally at or near the base. The column was thus broken only by its own inertia. The motion of the shaking table was automatically recorded, while the fracture of the column was carefully watched and its exact moment electrically recorded. The intensity of the motion, which caused the fracture, was then calculated from the diagram and compared with the theoretical value of the

1) For an account of similar experiments on a small scale, by Profs. Milne and Omori, see *Seism. Jour. Japan*, Vol. I.

2) In this connection, see also Omori, *On the Overturning and Sliding of Columns (caused by earthquakes)*. E. I. C. Publ., No. 12, pp. 8-27, or Hō., No. 32.

seismic stability of the column.

The amplitude of motion of the shaking table varied between 39.7 mm. and 128 mm., and fairly represented the motion likely to occur in strong and some destructive earthquakes. Further, as the period of the shaking table varied between 0.23 sec. and 0.89 sec., the maximum acceleration varied between 1570 mm. and 21,300 mm. per sec. per sec.; the motion may therefore be regarded as giving the intensity to be expected in any great earthquake. As however a few short columns could not be broken even with the most violent motion of the shaking table, we may reasonably conclude that *simple structures*, like columns, walls or bridge piers, can, when properly constructed, resist any destructive earthquake motion. All the other brick columns experimented upon were broken near, or at, the base; the columns being thus seismically weakest at their base, as is also theoretically evident.

As the brick column is fractured always at a joint, its seismic stability may be increased by using a good mortar, until the strength of the joint becomes equal to that of the bricks themselves.

One of the chief objects of the **fracturing experiments** was the comparison of the actual intensity of motion of the shaking table with the calculated values of the seismic stability of the column. The intensity, or the maximum acceleration A , of the shaking may be calculated from the amplitude and period of the shaking: the moment required; these two quantities. On the other hand

In the fracturing experiments so far made, the agreement between the quantities A and α was fairly satisfactory. Thus in a group of the experiments, the mean values of A and α were respectively 8610 and 8670 mm. per sec. per sec.

115. For given values of height and external dimensions, a hollow column has a greater seismic stability than the corresponding solid one; the sides or walls in the former column being sufficiently thick and rigid for it to be regarded as a single structure. In the case of columns with very thin walls, a slight irregularity in the joint may cause them to be fractured at accelerations much lower than those given by the theoretical formulae. Besides, with very thin columns, the mortar joint can not be made sufficiently strong, the adhesion between mortar and brick being perfect only along the middle zone of the joint. Similarly it has been found that, in cases of solid columns, the adhesion is not perfect along the edges of the joints adjacent to the free sides of the columns. These considerations indicate the danger of making a column or wall too thin. It seems, however, that the *principle of hollow column* may, with advantage, be applied to structures of large dimensions, such as the piers of bridges, in which the marginal effect would be trifling.¹⁾

116. *Overturning experiments* were made principally in connection with the determination of the intensity of motion of destructive earthquakes. Consequently the dimensions of the columns employed in the experiments have been of magnitude comparable to those of the stone lanterns, tomb-stones, etc., observed in actual cases.

Of the 42 columns experimented upon, two were iron pipes,

1) F. Omori: Notes on Applied Seismology, I. Verhandlungen der 1. internationalen seismologischen Konferenz, p. 398.

8 solid or hollow brick columns, 18 hollow columns or boxes of wood, and the remaining 14 solid columns of wood. The height of the columns varied between 1150 and 242 mm. and the dimension of the section between 300² and 90² mm.

The columns were put on the shaking table and overturned by giving proper movements to it. The shaking intensity deduced from the diagram of motion of the table was then compared with the theoretical values of the acceleration necessary for overturning the columns. In the experiments, the range of motion of the shaking table varied between 29.5 and 120 mm. and the period between 0.4 and 1.47 second; the maximum acceleration of motion varying between 750 and 10,700 mm. per sec. per sec. A wooden hollow column (242×242×484 mm.), however, could not be overturned even with the utmost intensity of motion at our disposal, which fact shows the difficulty of overturning of certain stable objects in earthquakes.

The overturning accelerations was found to be independent of the nature of the material of the columns.¹⁾

Vibrations of Bridge Piers.

117. Besides these experiments with small columns on a shaking table, and with some real chimneys, there is another method of investigating the nature of movements of such structures: namely, *to measure the vibrations of railway bridge piers caused by passing of trains over them.* This investigation is evidently important not merely in earthquake and typhoon countries in connection with the determination of their strength in resisting earth-

1) Omori: Seismic Experiments on the Fracturing and Overturning of Columns; E. I. C. Publ., No. 4, p. 137.

quake shocks and wind pressures, but as a general engineering problem.

The measurement was made by means of Prof. Omori's *Vibration measurer*, which is a seismograph slightly modified to suit the circumstances of the case. It consists of a helical spring vertical motion seismograph of the Gray-Ewing type, having a multiplication of 2, and a pair of horizontal pendulum seismographs, in which the weight of the bob is about 2 kg., and the distance between the two axes is 20 cm., having a multiplication of 1.5. The record is taken with ink on a band of paper wound round a drum driven at a rate of 12 to 25 mm. per sec., the time being measured by a small pendulum. The motion of a pier is thus recorded in three components, namely, the vertical, the transverse (or normal to the face of a pier), and longitudinal (or parallel to the face).

A vibration measurer for vertical component and that for a horizontal component are among the exhibits of the E. I. C. at this Exposition.

118. A preliminary series of experiments was carried on by Prof. Omori in 1901, on six different piers of four single track railway bridges in Central Japan. The results are reported in the E. I. C. Publ., No. 12, from which I make the following abstract.

The vertical vibration was always very small, while the transverse and longitudinal vibrations were usually well pronounced, their amplitudes being nearly equal to each other; the periods of the vertical and longitudinal vibrations were nearly constant, the mean values being 0.41 and 0.85 sec. respectively. These are probably not the periods of the true elastic vibrations of the piers themselves, but are rather those of the rocking motion of the latter due to the vertical and transverse vibrations

of the 200 feet girders which rest upon them. The maximum pier motion was 0.15 mm. for the vertical, and 1.2 mm. for the longitudinal component.

The periods of the transverse, or real elastic, motion of the different piers varied between 0.22 and 0.47 sec.; the maximum range of motion varying between 0.1 and 1.3 mm.

From what has been said above, it is evident that the periods of vibrations of the bridge piers are roughly speaking between 0.2 and 0.9 sec., that is to say, not very much different from the periods of motion in ordinary weak and strong earthquakes. At the time of a destructive earthquake, the motion of the piers would be much greater than that caused by ordinary railway traffic and the period may become upward of 1 sec. As, however, the period of destructive earthquake motion is generally between 1 and 2 sec., we may conclude that the bridge piers are likely to be fractured at the base.

In the case of the Ibi-gawa bridge (near Kuwana) the movements of the piers caused by *strong winds* were nearly the same as those due to the actual passage of the trains. In very violent storms, the motion would be much greater and the range of the transverse and longitudinal vibrations of such piers may, when coupled with those produced by the passage of a train, amount to a few mm.

Iron frames. The two piers, Nos. 4 and 5, of the Ibi-gawa bridge (near Kuwana) are nearly alike, except that the former has elliptical iron frames embedded in the well. The motion of the No. 4 pier was, however, not less than that of the other. This seems to show that iron frames, unless very strong, have no sensible effect on the vibrations of large masonry columns in which they are embedded.

A striking fact is that the motion of a pier does not always depend simply on its height above the well. Thus the motion of the pier of the Kizu-gawa bridge, whose height was 60 feet, was markedly smaller than that of those of the Tone-gawa (near Toride) and the Ibi-gawa (near Kuwana) bridges, although in the cases of the two latter bridges the heights of the piers above the river bed were only about 20 feet. The motion of the pier of the Tone-gawa bridge (near Maebashi), whose height is 40 feet, was also very small. These peculiarities are obviously due to the fact that the river beds of the Kizu-gawa and the Tone-gawa (near Maebashi) are hard, while the beds of the Ibi-gawa (near Kuwana) and the Tone-gawa (near Toride) are muddy and very soft. In other words, the piers with solid foundations are rigid; while those, whose foundations are weak, are very shaky.

From the above it is evident that a pier does not, in general, behave as if it were rigidly fixed to the ground at the surface of the latter. An approximate calculation shows, for instance, that one of the piers of the Tone-gawa bridge (Toride), whose well sinking amounts to 64-86 feet, must vibrate about a point in it some 45 feet below the ground surface as centre.

Deflection and Vibrations of Railway Bridges.

119. Another set of experiments to ascertain the effects of shaking on engineering structures was to measure the deflection and vibration of a railway bridge caused by the passage of a train over it. This also is an instance of the application of seismometrical instruments to practical purposes which are useful in non-seismic countries as well; for the determination of the de-

flection and vibrations of a bridge gives a criterion of the strength of the latter, and accordingly a comparison of the results obtained from a number of differently constructed bridges may lead us to the best form, in which the economy of material is combined with the strength of structure; and besides, these experiments enable us to know the variation of the strength of a bridge with time and load.¹⁾

120. The instruments used in these measurements were Prof. Omori's *Deflectograph* and *Vibration Measurer*, the latter of which I have already described [Art. 117]. The deflection was measured as a very slow vertical vibration; and the deflectograph is nothing more than the helical spring vertical motion seismograph, of the type described in Art. 44, with some improvements in the construction in order to reduce the friction between parts of the instrument and bring the steady point very near to the state of neutral equilibrium, so as to lengthen the period of the proper oscillation of the pendulum. The springs are suspended from a small cast-iron stand, about 60 cm. in height, fixed to a strong rectangular wooden plate about 30 × 60 cm. in size, on which the record-receiver is mounted. The steady point is the centre of a small horizontal lead cylinder about 1 kg. in weight, which is properly fixed near the end of a horizontal bar about 30 cm. long. With an apparatus of this dimension, the period of free oscillation of the steady mass can be raised, within the limit of stability, to about 12 seconds.

For reducing friction, a mode of attachment of the writing pointer to the steady mass, the same as in Prof. Omori's horizontal pendulum seismograph [Art. 39], is employed. The multiplication was 1 for a 200' span truss, and 2 for a 100' span truss or plate girders.

1) F. Omori : On the Deflection and Vibration of Railway Bridges ; E. I. C. Publ., No. 9.



Fig. 52. Deflectograph set up on a Bridge Girder.

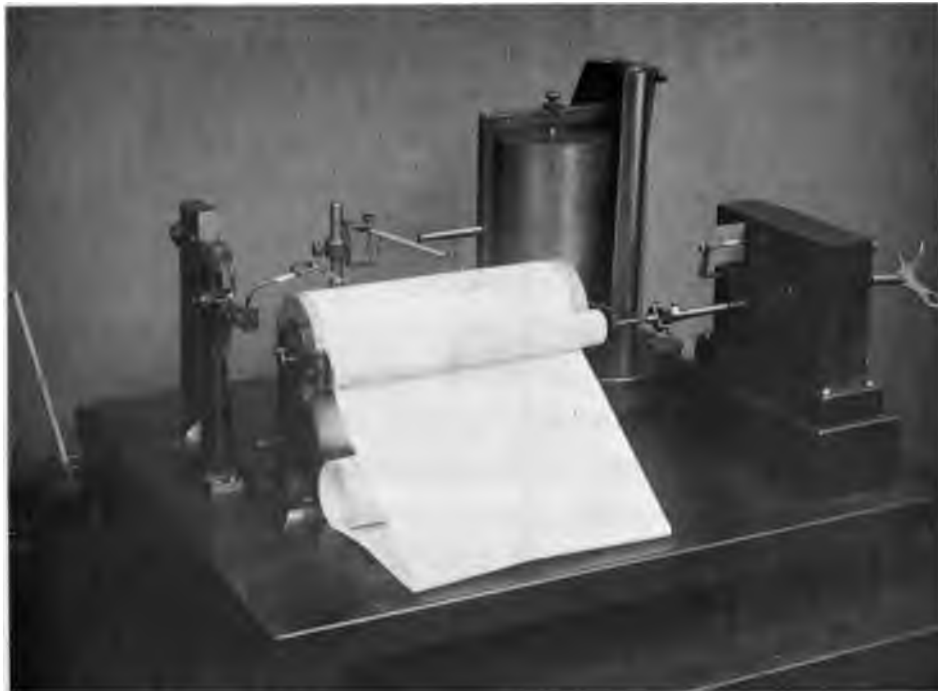


Fig. 53. Horizontal Tremor Recorder.

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In some cases the instruments can be fixed most conveniently in the box of one of the bottom chords. But in some trusses and plate girders, we must set up the apparatus within the stringer or the girder itself, below the rails and sleepers, the observer himself getting also therein and waiting the passage of the train overhead. The measurement, which requires no support to be erected from below, is possible even when there is abundant water underneath or when the bridge is high.

Prof. Omori has also devised a simple contrivance, by which the deflection of a bridge can be measured, even in cases when the engine remains stationary on the girder. [This will be described in a future number of the E. I. C. Publ.]

121. An account of the measurements of the deflection and vibration of 11 railway bridges made by Prof. Omori is given in E. I. C. Publ., No. 9, (also in E. I. C. Hō., No. 37); and the results of further experiments on 24 other girders and trusses are given in E. I. C. Hō., No. 45.

Some of the results obtained are as follows:

The 50' to 70' plate girders have shown nearly equal amounts of deflection and vibrations as the 100' Pratt trusses of the Chūbetsu and 3rd Ishikari-gawa bridges.

The vibrations of bridge girders caused by the passage of railway trains are their proper movements and have for a given load a period or periods of motion approximately constant for each of them; the period therefore does not depend on the velocity of the locomotives or on the distances between the wheels of the cars. The effect of the weight of the engine is to prolong the period by a small amount.

That a weak bridge girder has a slow period of oscillation, is well illustrated by the transverse vibrations of the 200' trusses of

the 1st Ishikari-gawa and the Ibi-gawa bridges. Thus the maximum length of the period was 1.06 sec. for the Ibi-gawa and 0.87 sec. for the 1st Ishikari-gawa bridge; and we find the maximum motion of 7.3 mm. for the former bridge and the maximum of 5.0 mm. for the latter.

To illustrate the relation between the strength of a given structure and the period of its vibration, suppose that there are two bridge girders, *A* and *B*, of exactly the same length and construction. If now the rivetting of *A* is better than that of *B*, then the girders may be looked upon as two elastic systems of equal mass, whose elastic moduli are unequal, *A* being more rigid than *B*. Consequently the girder *B* ought to have a longer period and be capable of being thrown into movements of greater amplitude, than the girder *A*.

From the considerations like these it is evident that the deflection and vibration experiments furnish us with criterions of the quality of bridges and like structures; the deflection being the test of strength, and the vibration that of rigidity.

Quite recently Professor Tanabe, of Kyōto Imp. Univ., has also measured the vibration and deflection of the newly constructed Kinogawa bridge. [Bulletin of the College of Science and Engineering, Kyōto Imp. Univ., Vol. I, No. 1.]¹⁾

122. The vibration measurer can also be made use of to record vibrations in *steamers* caused by the working of the engine, provided there be no great amount of pitching and rolling motion.

1) Before this, Prof. Ewing obtained statical diagrams of the horizontal movements of a bridge in Scotland, by means of a duplex pendulum seismograph. In Japan, Messrs. Milne and Macdonald measured the vibrations of several bridges on the Tōkaidō Railway, with glass-plate seismographs. The results of these measurements, however, must be received with caution, as the proper oscillation of the steady points themselves seems not to have been sufficiently considered.

These measurements will be useful to engineers for dealing with the vibration problem of steamers. In case of a man-of-war, it would be particularly interesting to measure the vibrations of decks caused by the discharge of guns. Recently measurements have been made by Professors Omori, Terano, Purvis and Shiba, of the vibrations of two torpedo destroyers and a torpedo boat, the results of which will be given in a forthcoming number of the *Journal of the Coll. of Engineering of Tōkyō Univ.*¹⁾

123. Yet another practical use of the vibration measurer is to record the vibrations of *railway carriages* and *locomotives*. This application of seismometry to practical engineering was first made by Prof. Milne, whose vibration recorder is, I understand, used by some railway companies for the examination of their lines. This instrument works fairly well and is extremely useful, but there is much friction among its parts, and the steady point has a too great stability, so that its period is often too short. Prof. Omori has made experiments with his vibration measurer, on several lines of railways, and obtained some important results, for which however I must refer you to the E. I. C. Publ., No. 15, or the *Hōkoku*, Nos. 40 and 42. Dr. Imamura has used the same vibration measurer for horizontal components, combined with Prof. Tanakadate's vertical motion seismograph, to measure the vibrations of electric tram cars.

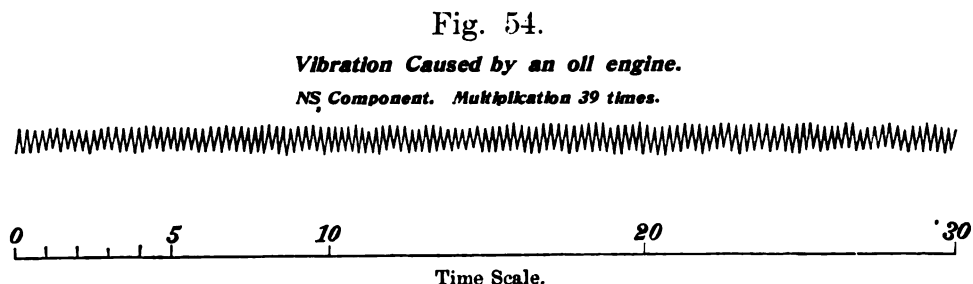
124. I have given several examples of the application of seismographs, sometimes slightly modified in details of construction, to measure various vibrations of structures, &c., not due to earthquakes. It seems needless to add that they have been used to measure vibrations of ground, due to causes other than seismic.

1) The measurements of ships' vibrations, which have already drawn the attention of European and American engineers, were before this tried by Herr Schlick and others.

Thus, they were employed by various seismologists to measure vibrations caused artificially by dropping heavy weights or by explosions of dynamite, &c. In some cases, especially in earlier days, the experiments were made to ascertain the nature of vibrations of the ground; later, they were made oftener for practical purposes, for finding the effects of explosions, &c.

123. Lately, a form of Omori's horizontal pendulum seismograph, called Horizontal Tremor Recorder and magnifying the motion from 50 to 70 times, has been employed for measuring the horizontal tremors of the ground or structures caused by the working of a steam engine, steam hammer, dynamo, &c., or by passing carriages and trains. They have been used by the Tōkyō Metropolitan Police in dealing with questions respecting disturbances due to causes above mentioned [see fig. 53]. One of these instruments is among the exhibits of the E. I. C. at this Exposition; a full description will be given by Prof. Omori in E. I. C. Publ., No. 18.

Fig. 54 is a part of the diagram obtained at the Seismological Institute, of the tremors caused by a small oil-engine of 10 horse power working at a distance of about 70 metres. Movements like these are extremely small and insensible, and yet they have often



the effect of causing window panes and doors to rattle, bottles on

table to shake, suspended articles to swing, &c., thus becoming a source of mystery to people in the neighbourhood.

Determination of Young's Modulus of Brick Columns.

126. In connection with the fracturing experiments, the horizontal pendulums were utilized for measuring Young's modulus of several brick columns, which were about 2 m. in height, their cross sections being 1 brick square.

The experiments consisted in measuring with a horizontal pendulum the terminal deflection angle of a column bent by a known weight. The bending was in several cases carried to the actual breaking; the relation of the stress to the strain remaining very nearly linear throughout. This means that the brick columns behave as an almost perfectly elastic body till they are fractured by bending, a conclusion which has an important signification in connection with the fracture of brick columns. The Young's modulus of several brick columns has been determined in this way. As far as the experiment goes, the highest and the lowest values of the modulus were as follows:—

$$\text{(highest)} \quad E = 10^{10} \times 4.596 \quad (\text{C. G. S. units})$$

$$\text{(lowest)} \quad E = 10^{10} \times 1.290 \quad (\quad , \quad).$$

As the period of free vibration of a given elastic body is inversely proportional to $\sqrt{E}$, the period of vibration, for instance, of a chimney, whose brick-work has its $E=10^{10} \times 1.29$ (C. G. S. units) would be about double that of another, similar to it, but made up of brick-work whose $E=10^{10} \times 4.596$ (C. G. S. units). This method of experiment is applicable, by increasing the sensitiveness

of the instruments, to columns of much greater cross section than those considered above.

1) Omori: Notes on Applied Seismology; Verhandlungen der 1. Internationalen Erdbeben Konferenz. p. 392.

CHAPTER VII. CONCLUDING REMARKS.

127. I have sought to give an epitome of the Recent Seismological Investigations in Japan. In our work we have been very much helped by the recent remarkable spell of seismic activity, both on account of the general interest excited, and also by the many excellent opportunities given to scientific men and engineers to study the seismic phenomena. We have now passed through the stage of first rough approximations in our investigations, and are about to enter upon the second approximations. Instead of groping almost in the dark, as in the early days, we now know more accurately what we need, and can better adjust our means to our wants. In many cases we have got the outline and shall have to fill in the details; in others we shall have to extend our results from particular to general, and so on.

128. Moreover, now that our improved seismographs show that earthquake waves are propagated to distant parts of the world, sometimes even more than once round the world, international cooperation has become desirable. The British Association for the Advancement of Science has done well in inviting the cooperation of different countries in seismological work; but something more than a private enterprise, an international organisation with nations contributing, is necessary for a work of this kind; and I am glad to say that an International Seismological Association is now in course of organisation. This association will no doubt concern itself primarily with the investigation of the movements of the earth's crust, sensible and insensible,—the nature

and relations of these movements, the path, velocity, and mode of propagation of their waves, and the methods of observing them. The B. A. A. S. laid much stress on making observations with *similar* instruments; but this seems to be by no means so essential: what is important, is rather that the peculiarities of each instrument, such as its proper period, the degree of damping, and the amount of friction between the parts (whether rolling or sliding), &c. should be definitely known and carefully considered in discussing the records.

I am glad to see however that the International Seismological Association will not confine itself simply to the observation of earth motion and to its discussion: it should, either by itself or in cooperation with other bodies, occupy itself with all the principal problems relating to Seismology.

129. It appears that the seismic and volcanic activity is not generally manifested in an isolated manner nor confined to a small part of the world, but rather tends to occur in groups, and often simultaneously in distant parts of the world. Thus, in the nineties, we had, in Japan, a series of large and destructive earthquakes, volcanic eruptions, tsunamis, &c.; during the single month of Sept., 1899, there were 4 large earthquakes in different parts of the world; viz. two in Alaska, one in Asia Minor, and one in Ceram. Are these mere coincidences, or is there some relation between them?

With regard to earth magnetism, it may be that not merely local disturbances but widespread ones also have some connection with seismic activity; it would be as rash to assume that because a magnetic disturbance was observed over a large part of the world, therefore it had no connection with the seismic disturbance at any *one* spot, as that a local magnetic disturbance has a necessary

connection with an earthquake near to the disturbance in time and space. It will require a most careful and extensive examination before these relations can be accepted or rejected. It is possible that both of these phenomena as also Volcanic Activity, Variation of Latitude, &c. may be different manifestations of one and the same cause.

I have stated what we have been doing in Japan to find out the relations of the seismic with other phenomena, such as the Seasons, the Changes of Barometric Pressure, the Phases of the Moon, the Changes of Underground Temperature, &c. Among them, some seem to be fairly well established, although their exact determination must await future observations; while others are still doubtful and will require further examination.

There are other physical determinations, such as Gravity, the Elastic Constants of Rocks, and their Thermal Conductivity, the Elastic properties of the Earth's crust, &c., eminently useful to seismologists.

I do not speak of Geology, the importance of which is obvious; what seismologists want to know above all things is the geotectonic nature of the region concerned, for on this must depend its seismic character. In fact, it is as a means of getting an insight into this and the stresses in the earth's crust that the seismologists want the determinations of physical phenomena above mentioned. In a word, pure Seismology is a branch of Geophysics, the Dynamics of the Earth's crust, so to speak.

130. On the other hand, seismology has rendered service to pure physics in several ways, among others, in calling the attention of physicists to the necessity of not overlooking the effects of insensible but by no means very small movements of the earth's crust in delicate physical determinations: Prof. Nagaoka mentions an

interesting instance in which the pendulum experiments for the determination of gravity in Tōkyō were affected by insensible movements of the earth, due to a great earthquake originating off the south-western coast of Alaska.¹⁾

131. With regard to the prediction of earthquakes, it is not to be expected that the E. I. C. should be able to accomplish so difficult a task within so short a time, but there is no reason to assume that by further perseverance in the same and other investigations, we shall not finally arrive at this desired goal.

On the practical side, the E. I. C. has done work of much importance in an earthquake country like Japan. Some of the results however are not confined, in their application, to earthquake countries; the determinations of the vibrations of railway bridge piers, of the deflection and vibrations of girders and trusses, of vibrations of railway and electric cars and of ships, will be of interest and use to engineers in all parts of the world.

132. The study of Seismology is a fascinating one, but to us who are living in a country like Japan, it is not merely of theoretical interest, but of great practical importance. We have so far done our best to advance its knowledge, and we have got over the first stage; and now that the cooperation of the whole world is in a fair way to be established by the organisation of an International Seismological Association, I trust, we shall not be wanting in doing our proper share of the work, large as that share should be; more especially, is it our part to assist in the province of the Macro-seismic Investigation, considering that no other country has such an unenviable preëminence in the matter of earthquake frequency.

1) Jour. Sc. Coll., Vol. XVI, Art. 11, p 17.

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 “THE PUBLICATIONS OF THE EARTHQUAKE
 INVESTIGATION COMMITTEE IN
 FOREIGN LANGUAGES.”

(Referred to as the E. I. C. Publ.)

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